

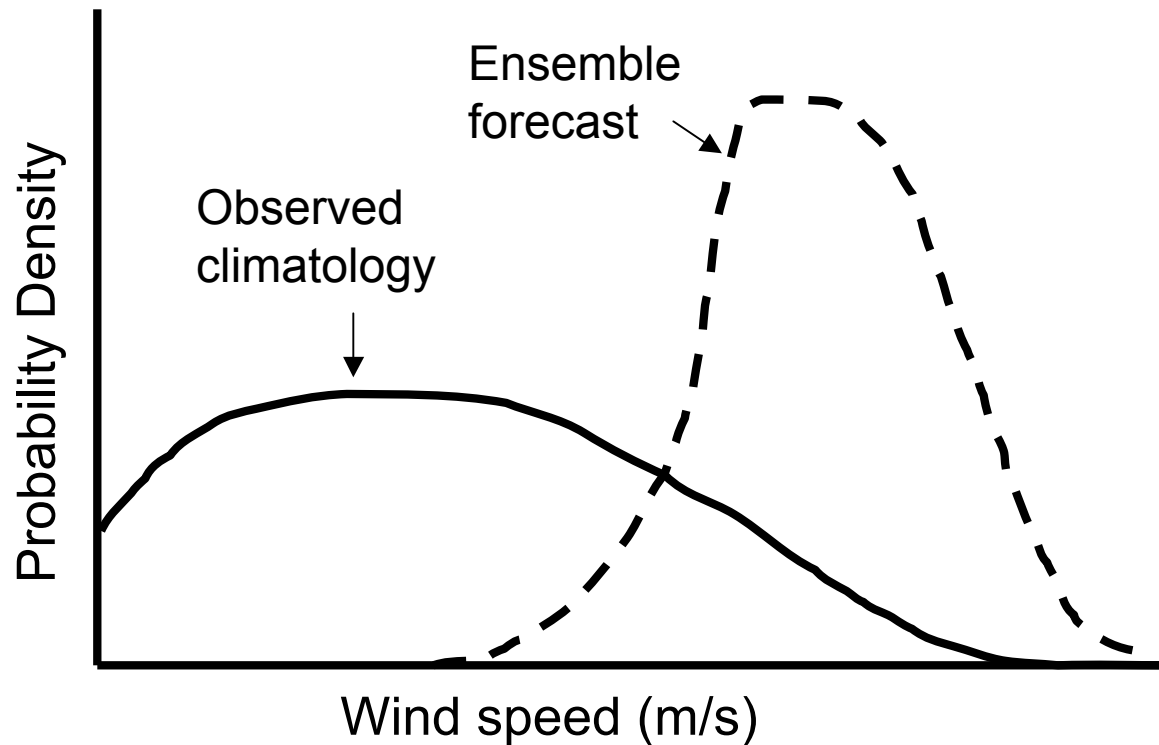
Severe-weather and extreme-event forecasting using ensembles

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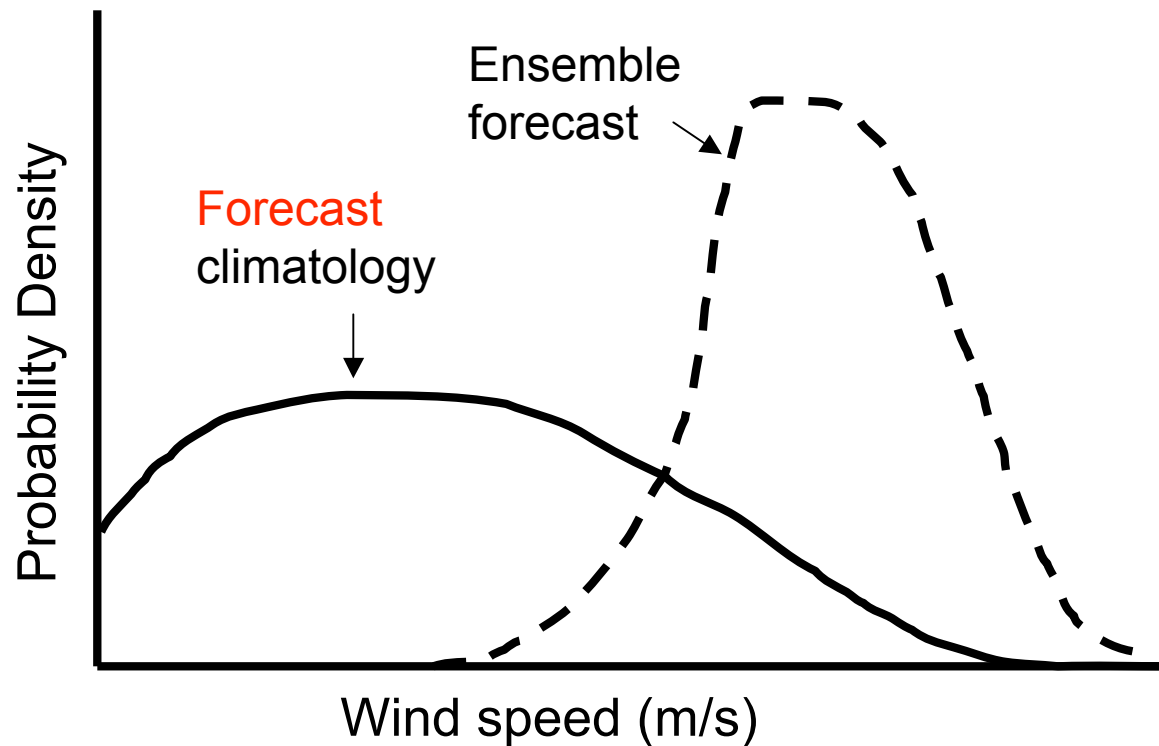
tom.hamill@noaa.gov

Is this a predictable extreme event?



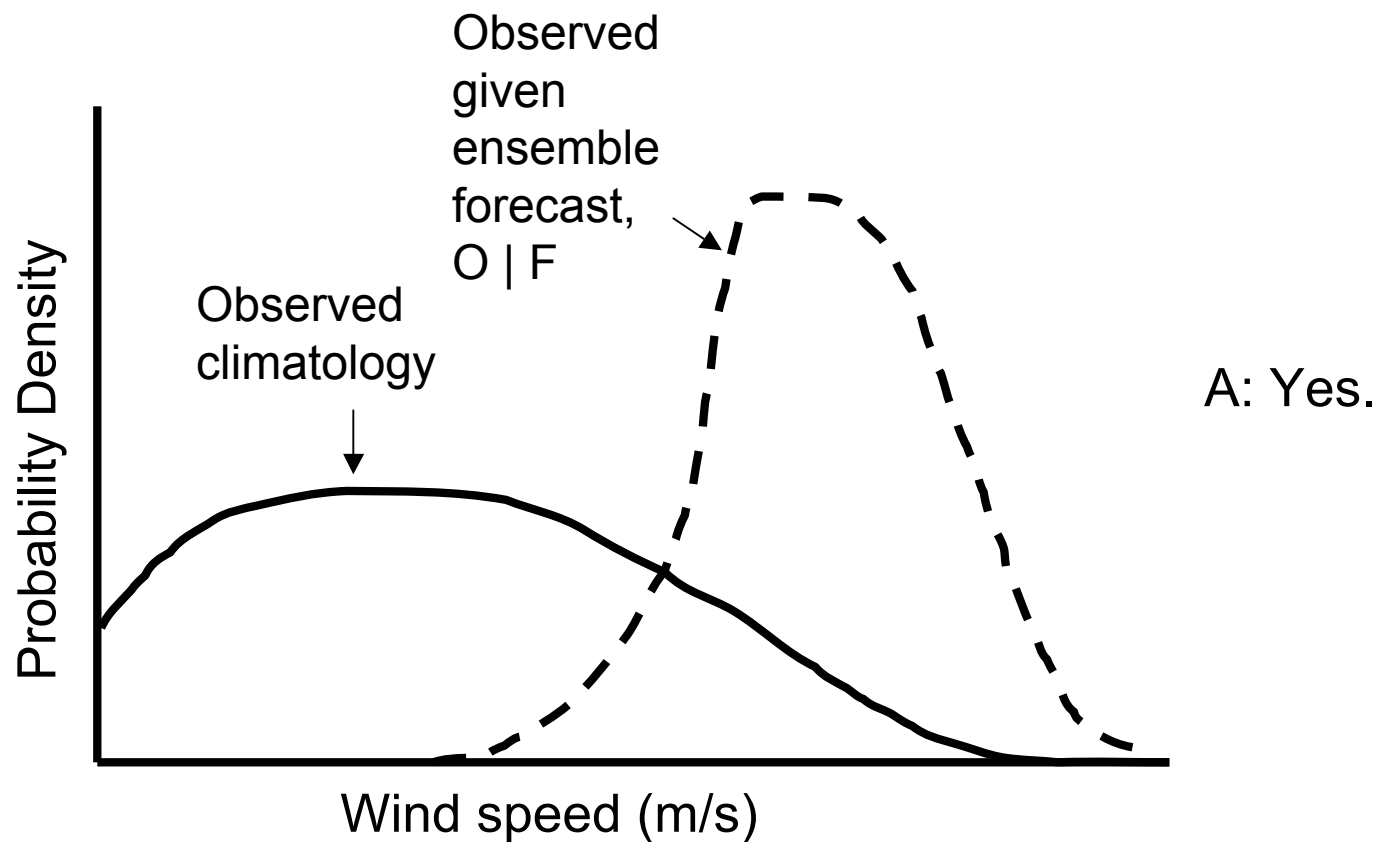
A: Not necessarily so. Perhaps the ensemble forecast is strongly biased toward high wind speeds.

Is this a predictable extreme event?



A: Not necessarily so. Is there a strong correlation between F' and O' , so that a high forecast anomaly indicates a high observed anomaly?

Is this a predictable extreme event?



Some general characteristics of predictability

- If extreme event large in scale, or driven by large scales, or if there strong flow to sweep mesoscale perturbations away from convective source region → possible days of predictability.
- Not driven by large scales → more classical Lorenz '69 predictability → hours of predictability. Also, model errors may be more pronounced.

Example of possible extended mesoscale predictability: SREF probability of “significant tornado”

48 hr SREF Forecast Valid 21 UTC 7 April 2006

Prob (MLCAPE $\geq 1000 \text{ Jkg}^{-1}$)

X

Prob (6 km Shear $\geq 40 \text{ kt}$)

X

Prob (0-1 km SRH $\geq 100 \text{ m}^2\text{s}^{-2}$)

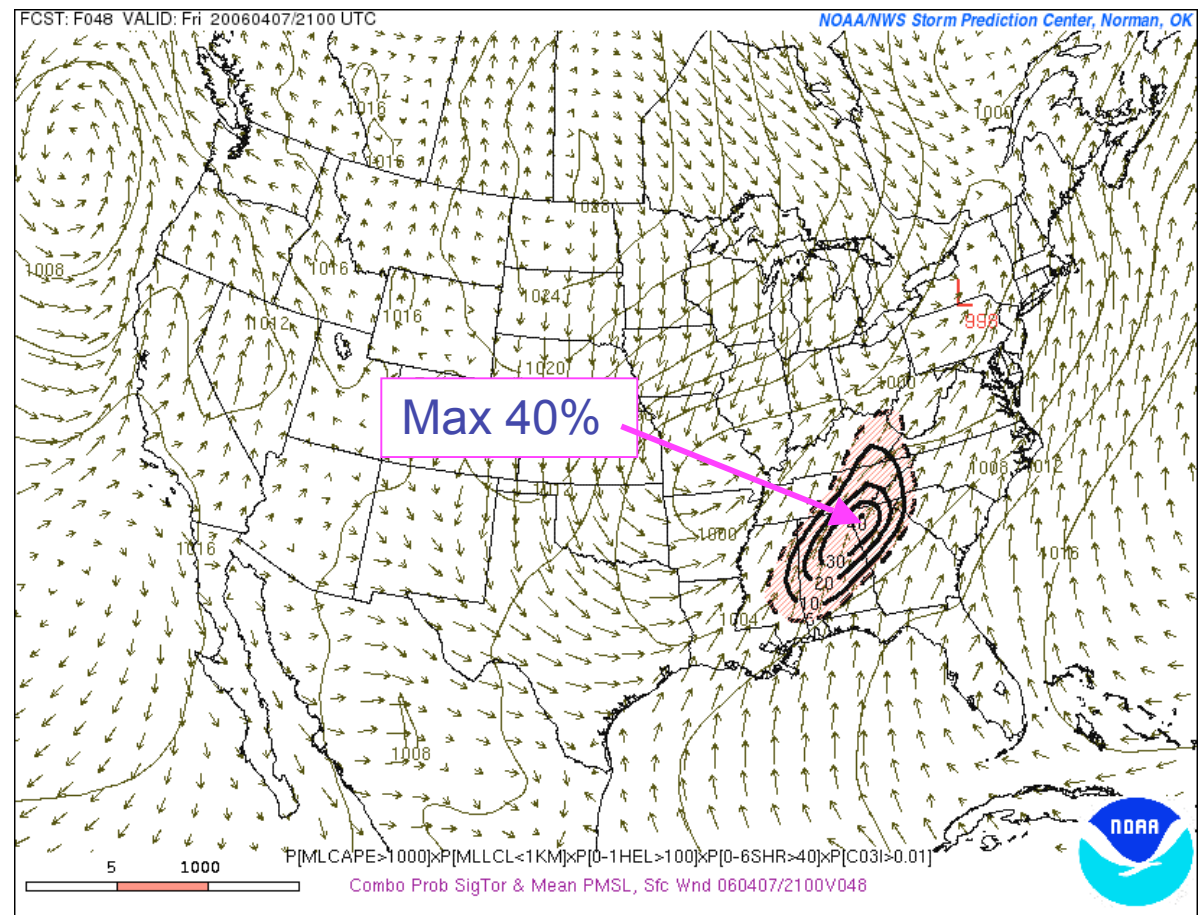
X

Prob (MLLCL $\leq 1000 \text{ m}$)

X

Prob (3h conv. Pcpn $\geq 0.01 \text{ in}$)

Shaded Area Prob $\geq 5\%$



6

(MLCAPE = CAPE using lowest 100 hPa)

Example from David Bright, SPC, using Jun Du's NCEP SREF system

Example of possible extended mesoscale predictability: SREF probability of “significant tornado”

36 hr SREF Forecast Valid 21 UTC 7 April 2006

Prob (MLCAPE $\geq 1000 \text{ Jkg}^{-1}$)

X

Prob (6 km Shear $\geq 40 \text{ kt}$)

X

Prob (0-1 km SRH $\geq 100 \text{ m}^2\text{s}^{-2}$)

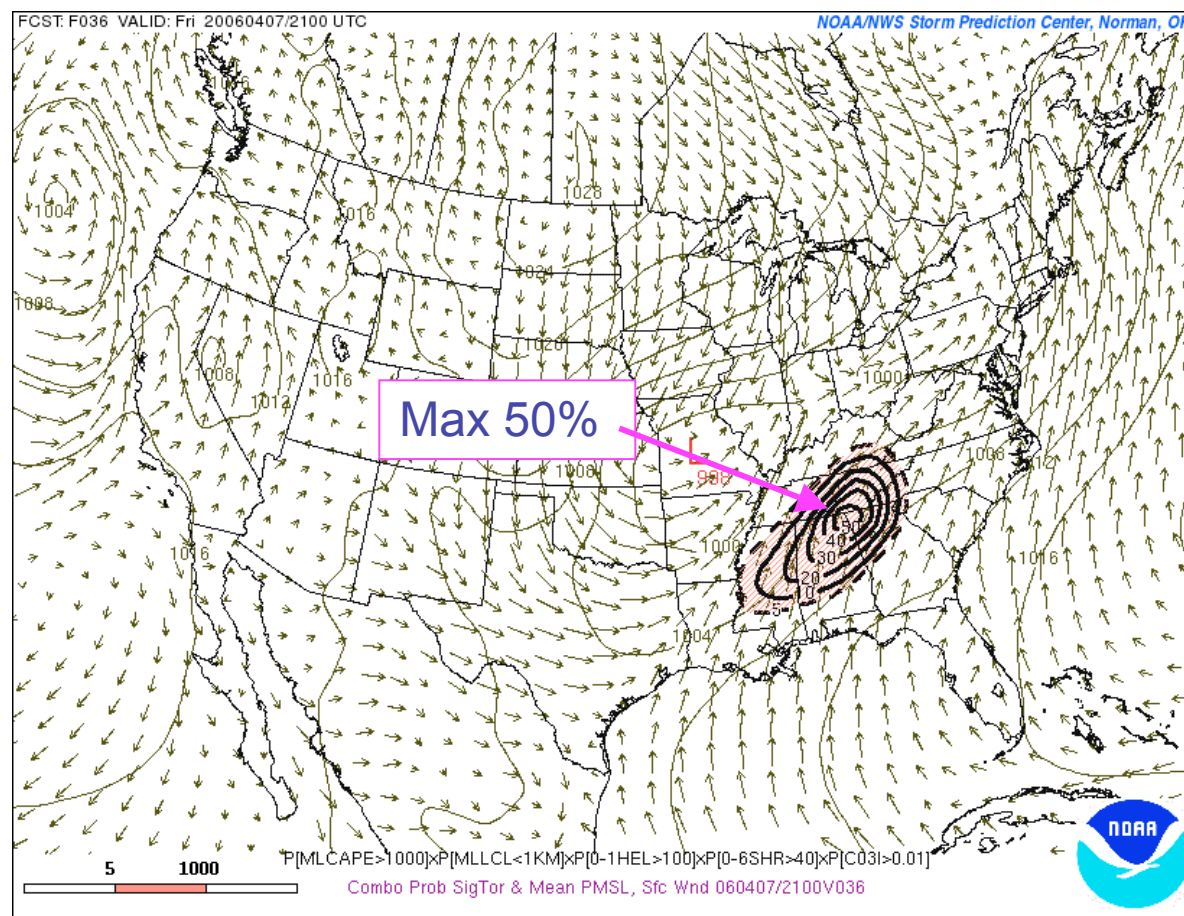
X

Prob (MLLCL $\leq 1000 \text{ m}$)

X

Prob (3h conv. Pcpn $\geq 0.01 \text{ in}$)

Shaded Area Prob $\geq 5\%$



Example of possible extended mesoscale predictability: SREF probability of “significant tornado”

24 hr SREF Forecast Valid 21 UTC 7 April 2006

Prob (MLCAPE $\geq 1000 \text{ Jkg}^{-1}$)

X

Prob (6 km Shear $\geq 40 \text{ kt}$)

X

Prob (0-1 km SRH $\geq 100 \text{ m}^2\text{s}^{-2}$)

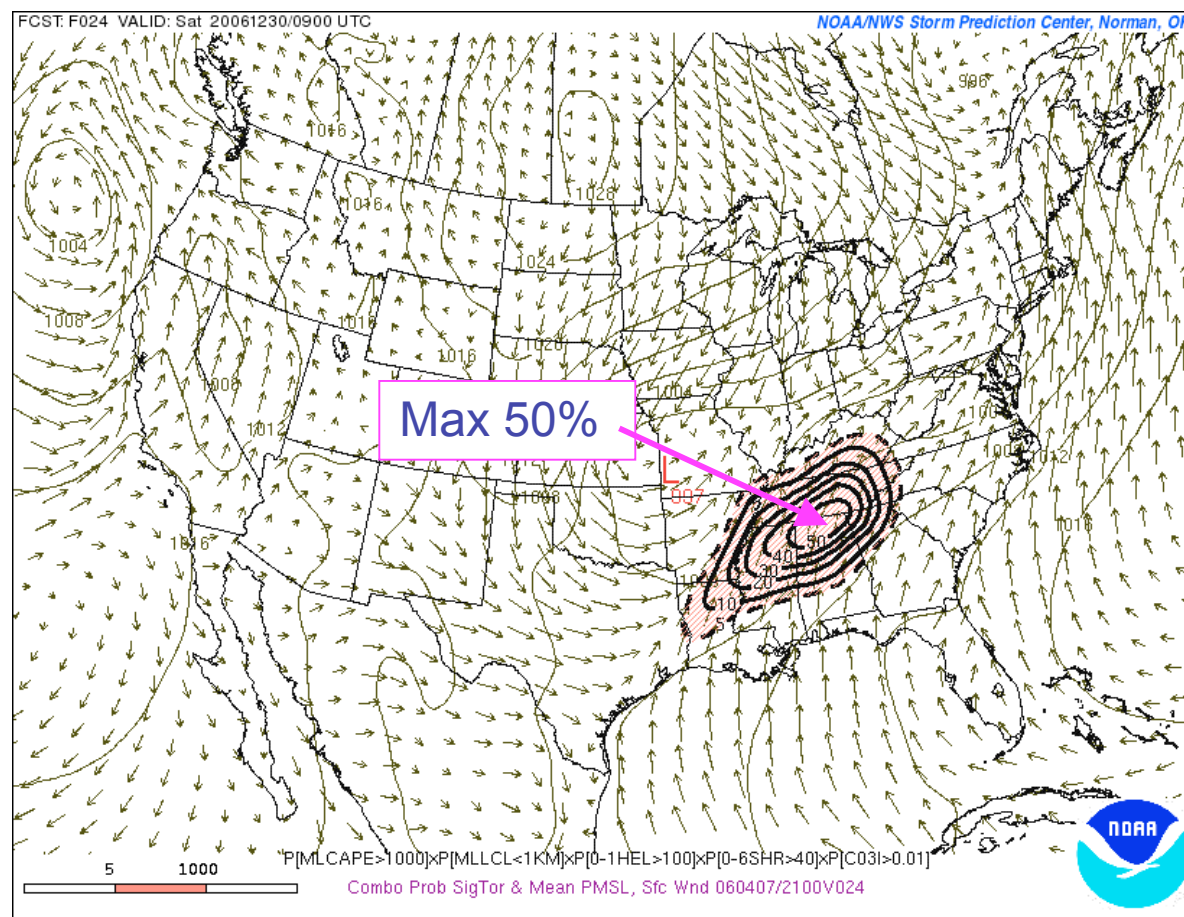
X

Prob (MLLCL $\leq 1000 \text{ m}$)

X

Prob (3h conv. Pcpn $\geq 0.01 \text{ in}$)

Shaded Area Prob $\geq 5\%$



Example of possible extended mesoscale predictability: SREF probability of “significant tornado”

12 hr SREF Forecast Valid 21 UTC 7 April 2006

Prob (MLCAPE $\geq 1000 \text{ Jkg}^{-1}$)

X

Prob (6 km Shear $\geq 40 \text{ kt}$)

X

Prob (0-1 km SRH $\geq 100 \text{ m}^2\text{s}^{-2}$)

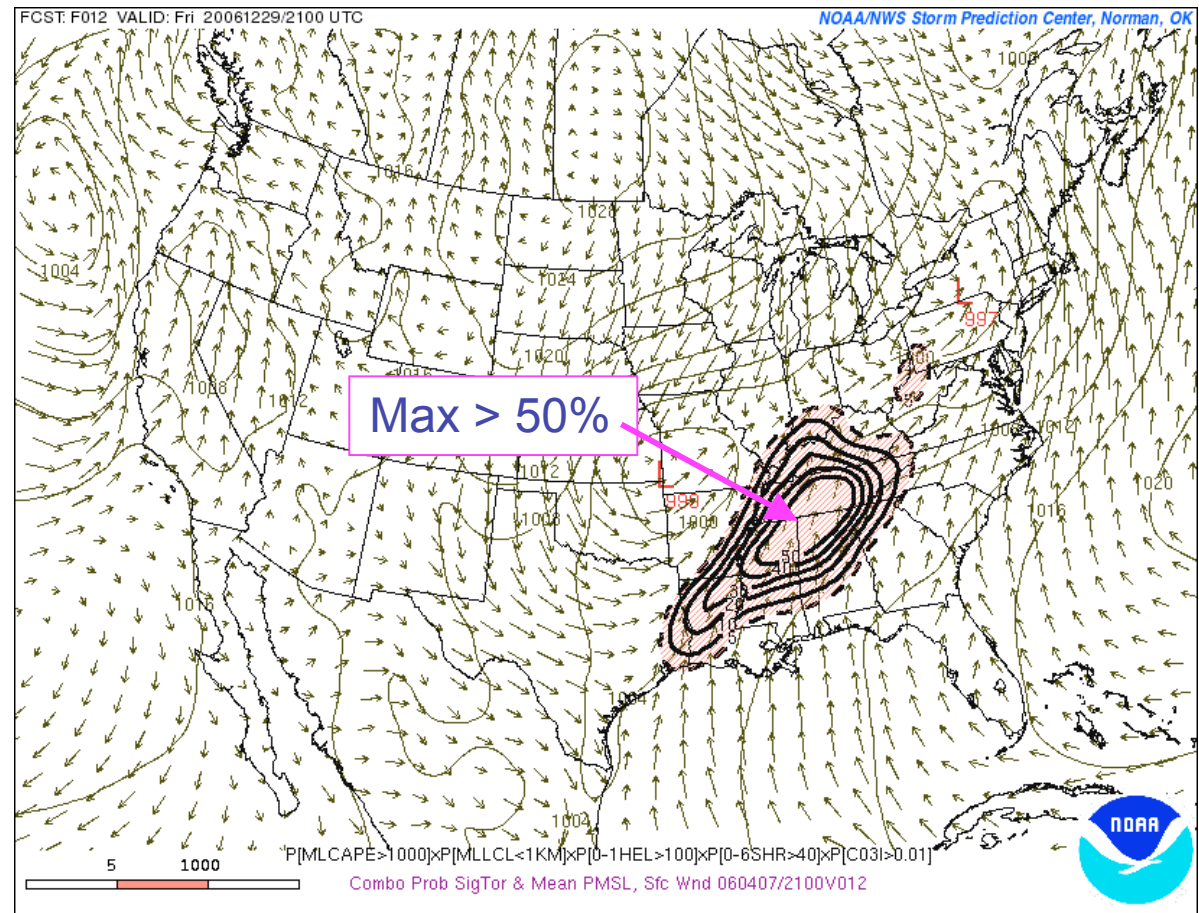
X

Prob (MLLCL $\leq 1000 \text{ m}$)

X

Prob (3h conv. Pcpn $\geq 0.01 \text{ in}$)

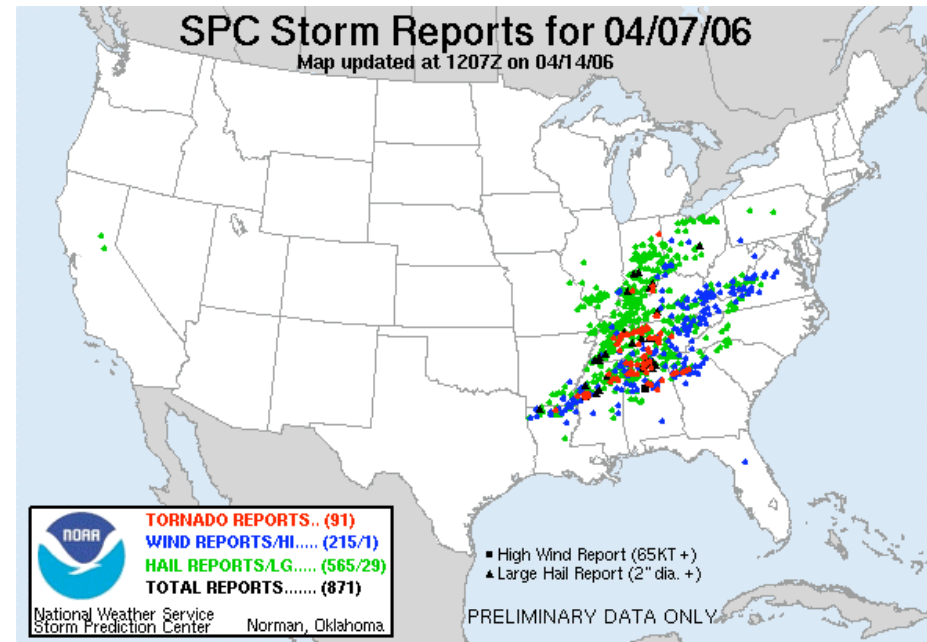
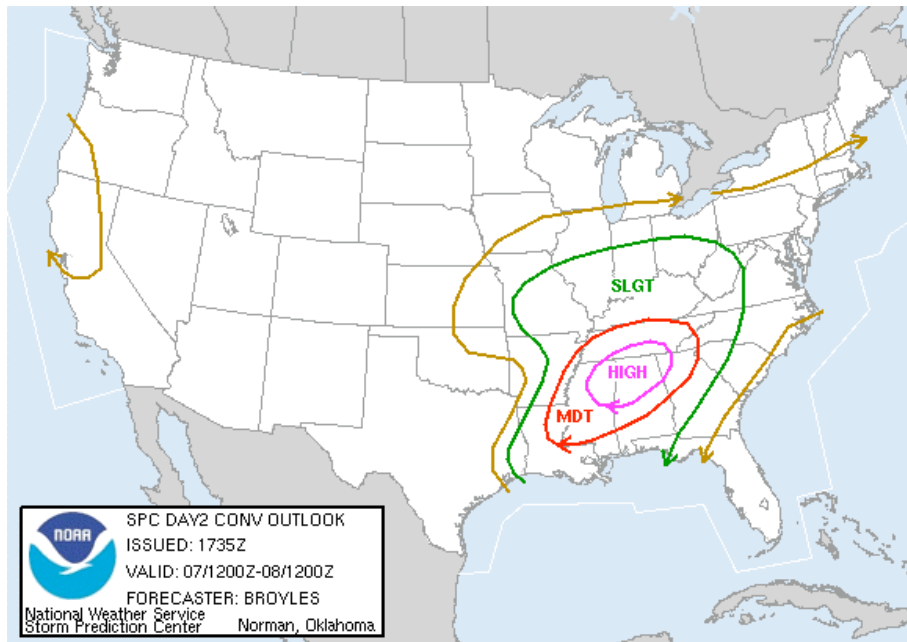
Shaded Area Prob $\geq 5\%$



Tornadoes related to large-scale patterns of instability and shear, often predictable several days hence.

Severe event of April 7, 2006

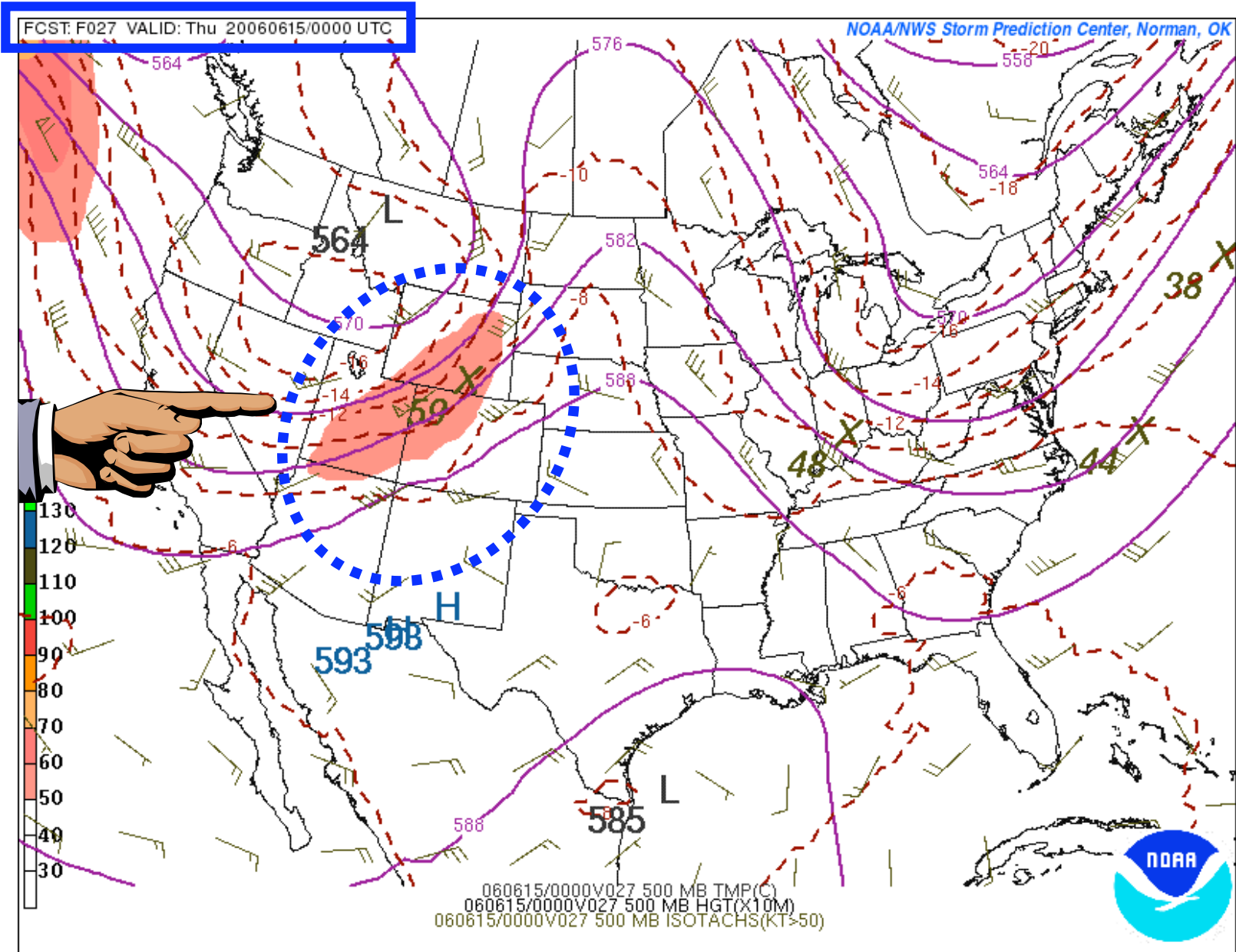
- **First ever** day-2 outlook “high risk” of severe weather issued by NOAA Storm Prediction Center; in past have been cautious
- > 800 total severe reports, 3 killer tornadoes, 10 deaths
- Diagnostics from SREF and good past SREF performance aided forecaster confidence



Example of predicting extreme event from ensemble: US fire-weather forecasting

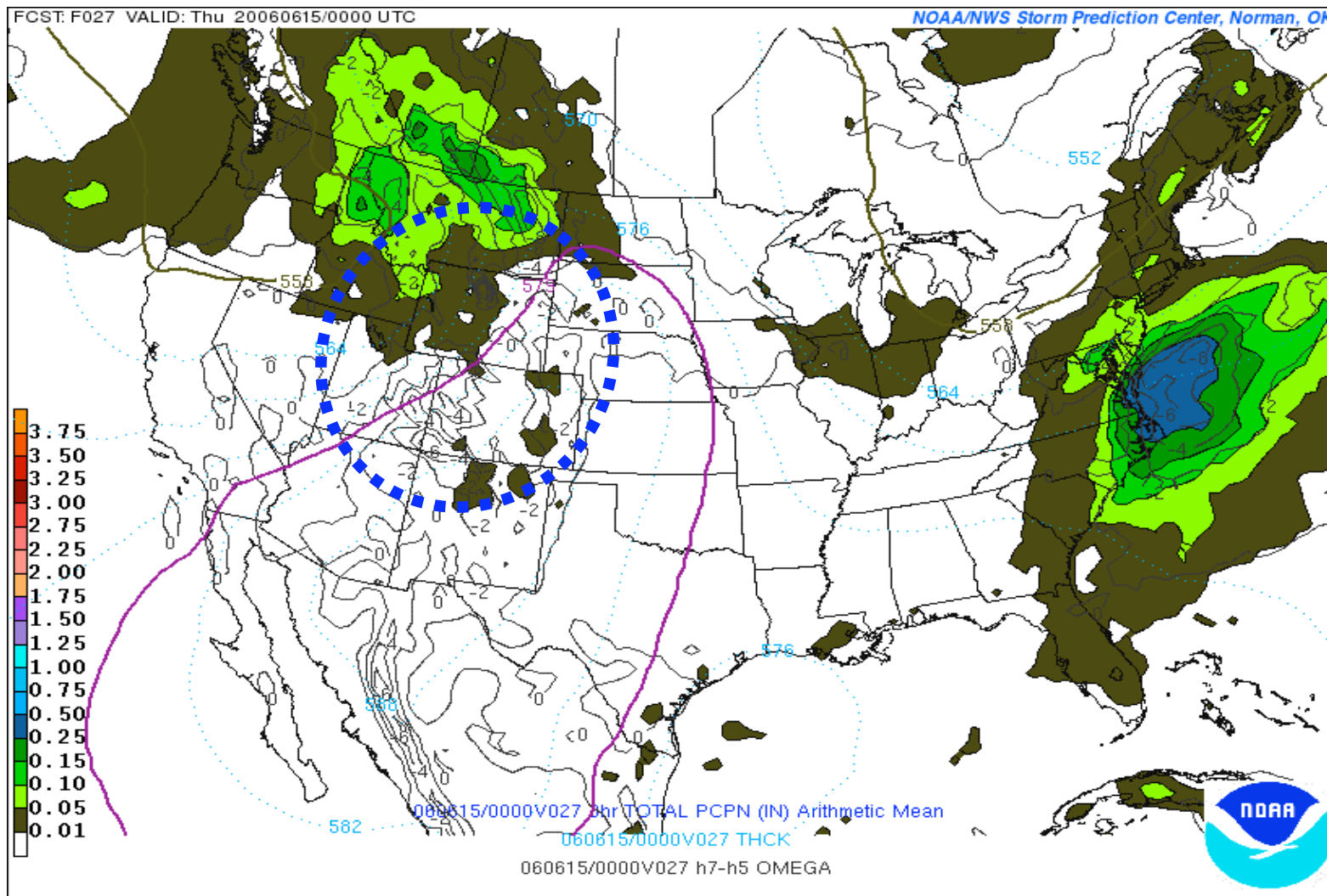
- Ingredients from large-scale conditions:
 - High wind speeds
 - Hot temperatures
 - Low relative humidity near surface
 - Little rainfall

SREF 500 hPa mean height, wind, temperature



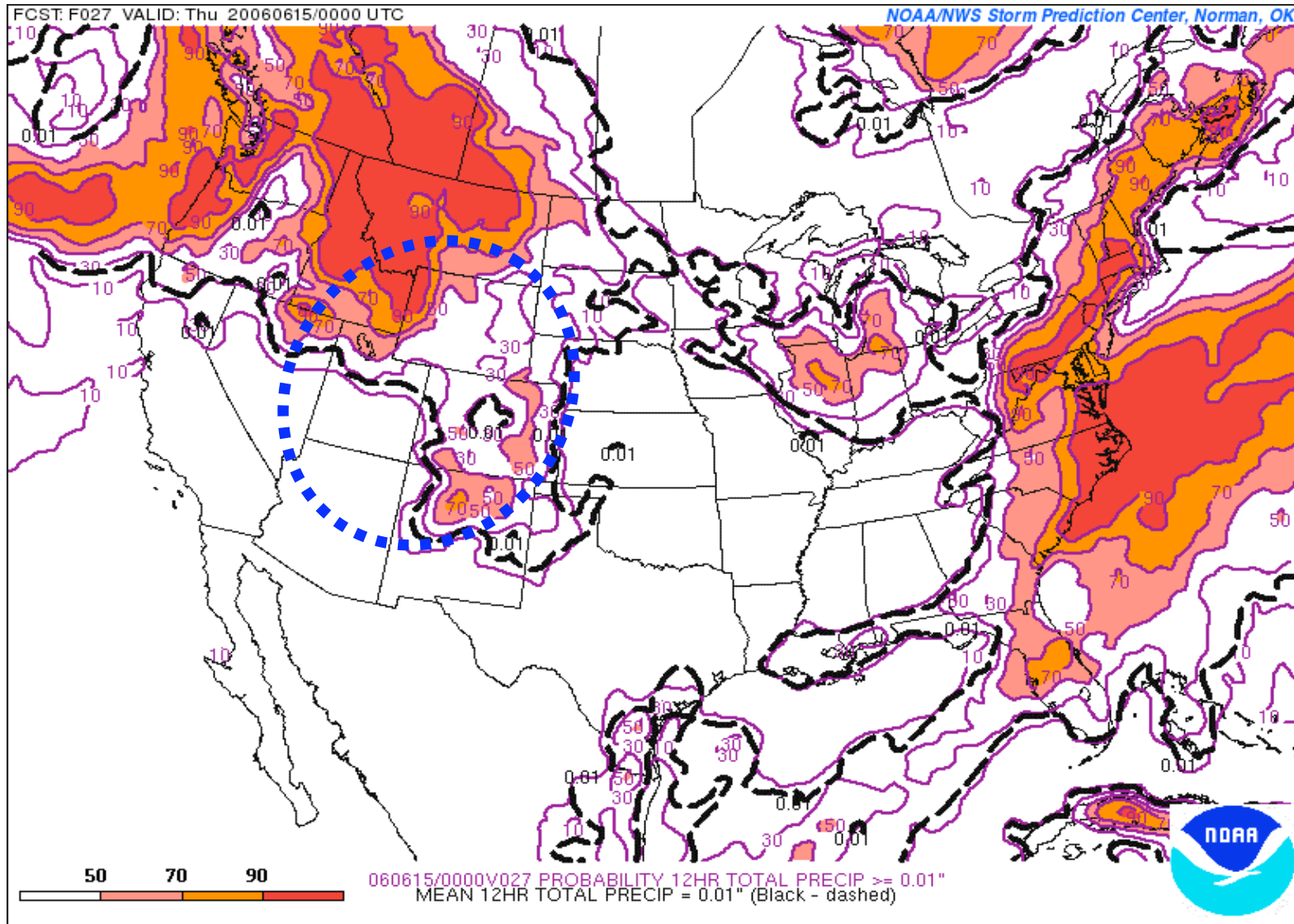
Following plots courtesy of David Bright, NOAA/NCEP/SPC, using Jun Du's NCEP SREF system

SREF mean precipitation, vertical velocity, thickness



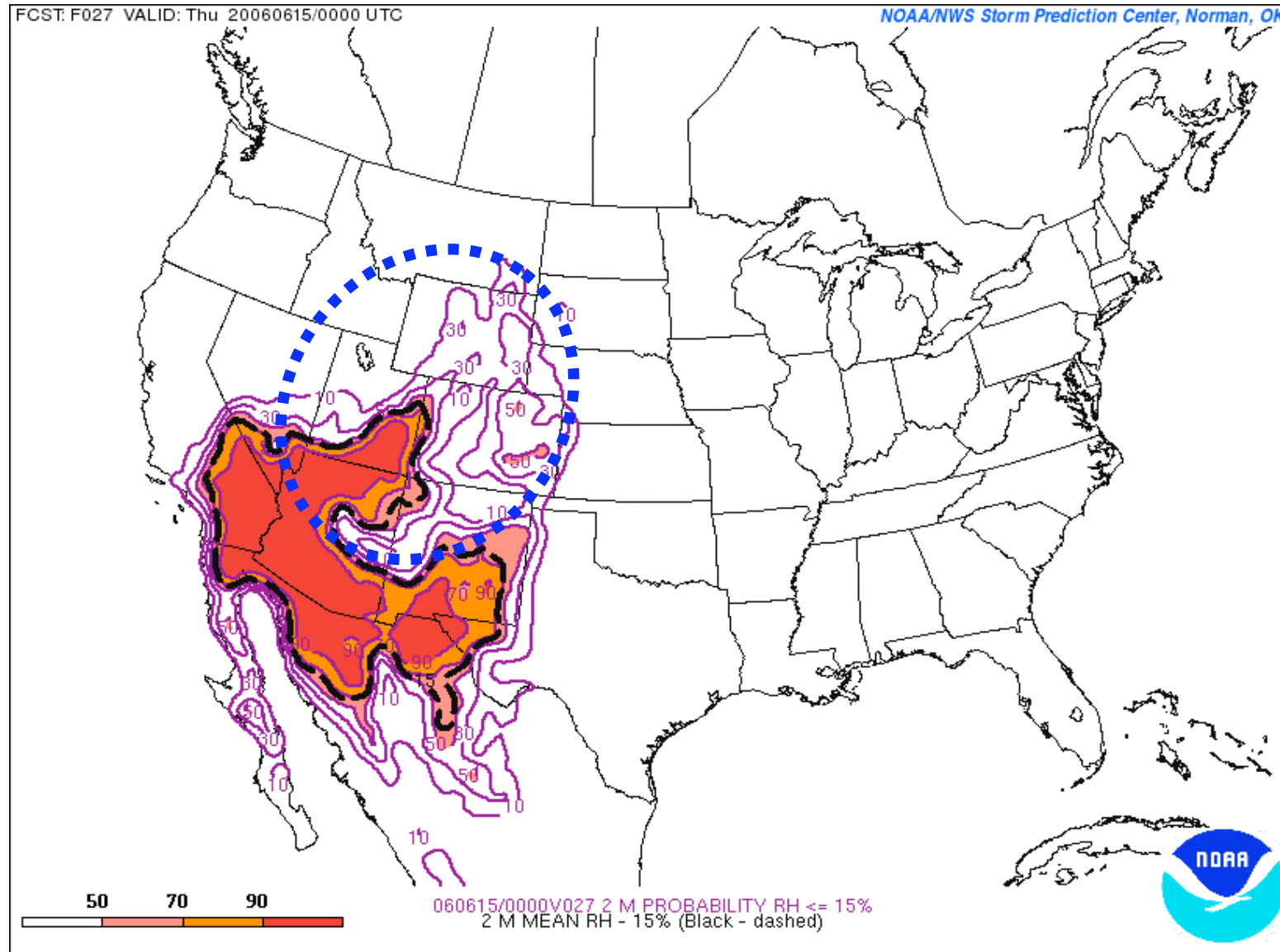
Over desert southwest US, little model forecast mean precipitation, and very warm conditions (purple is mean 5790 m 1000-500 hPa thickness).

SREF Pr[P12I \geq .01"] and Mean P12I = .01" (dash)



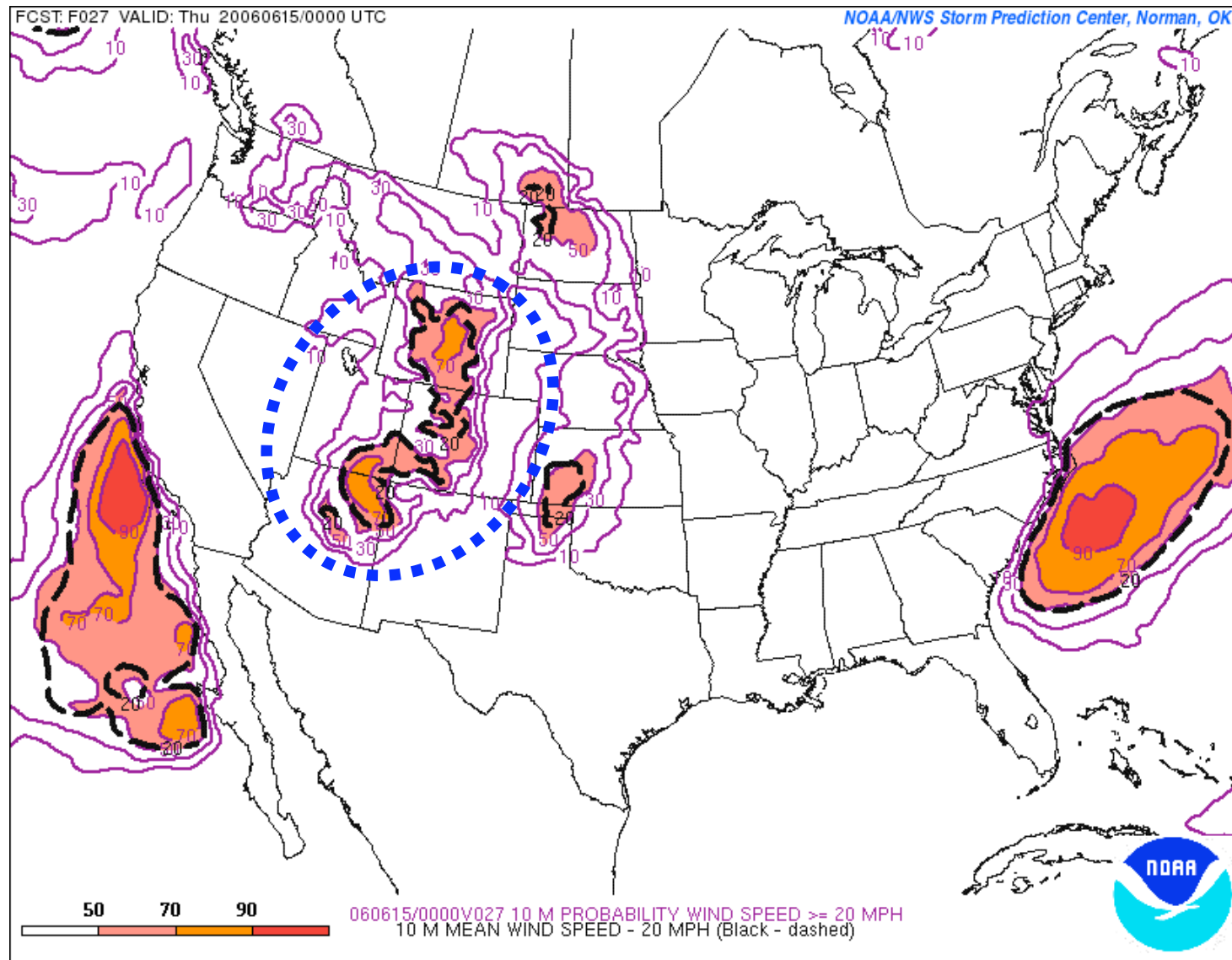
Some members forecasting precipitation over Colorado, New Mexico, but southern Utah and Arizona forecast dry.

SREF Pr[RH \leq 15%] and Mean RH = 15% (dash)



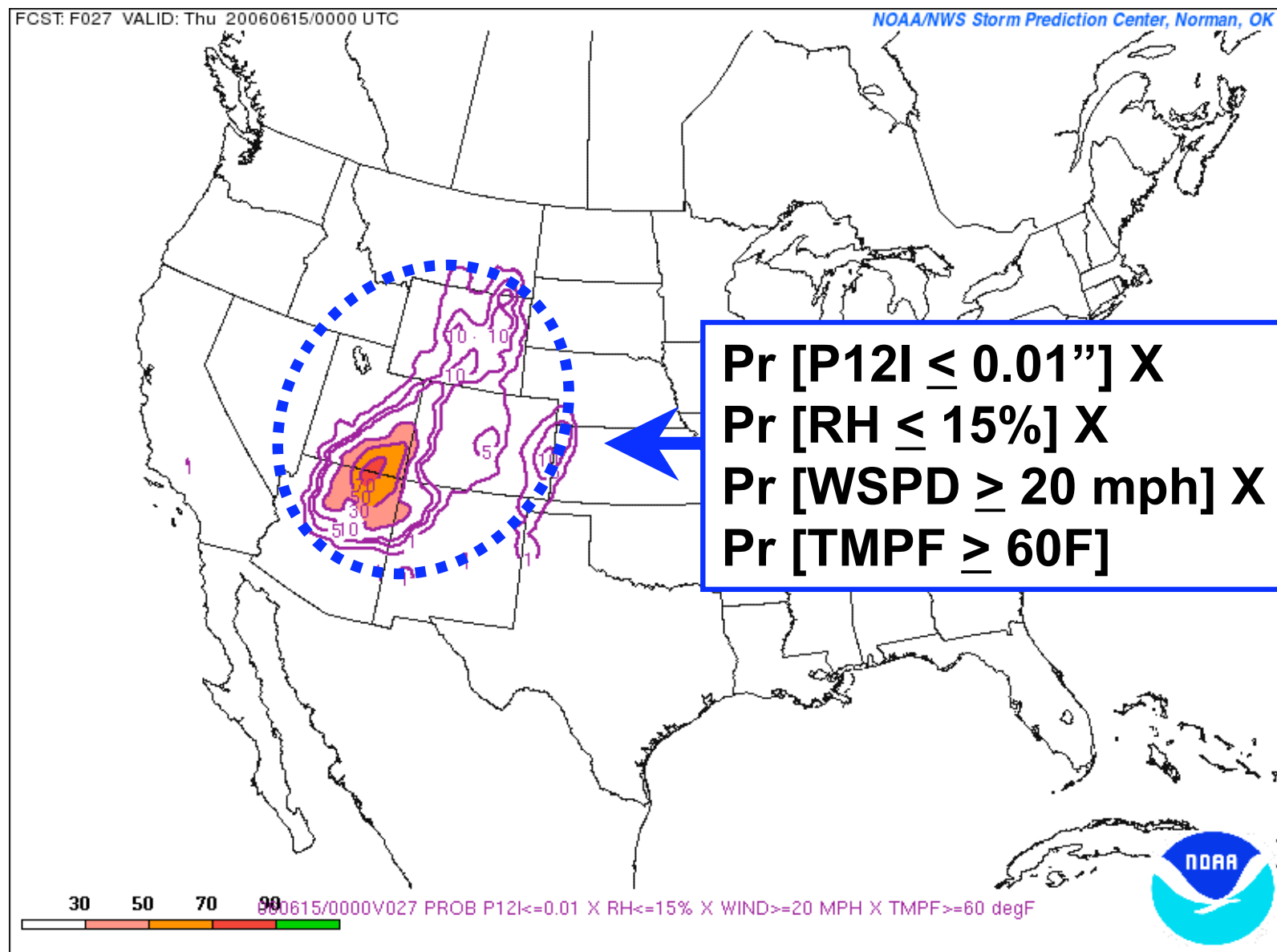
very low near-surface relative humidity over Arizona, southern Utah 15

SREF Pr[WSPD \geq 20 mph] and Mean WSPD = 20 mph (dash)



Many of the members are forecasting gusty winds.

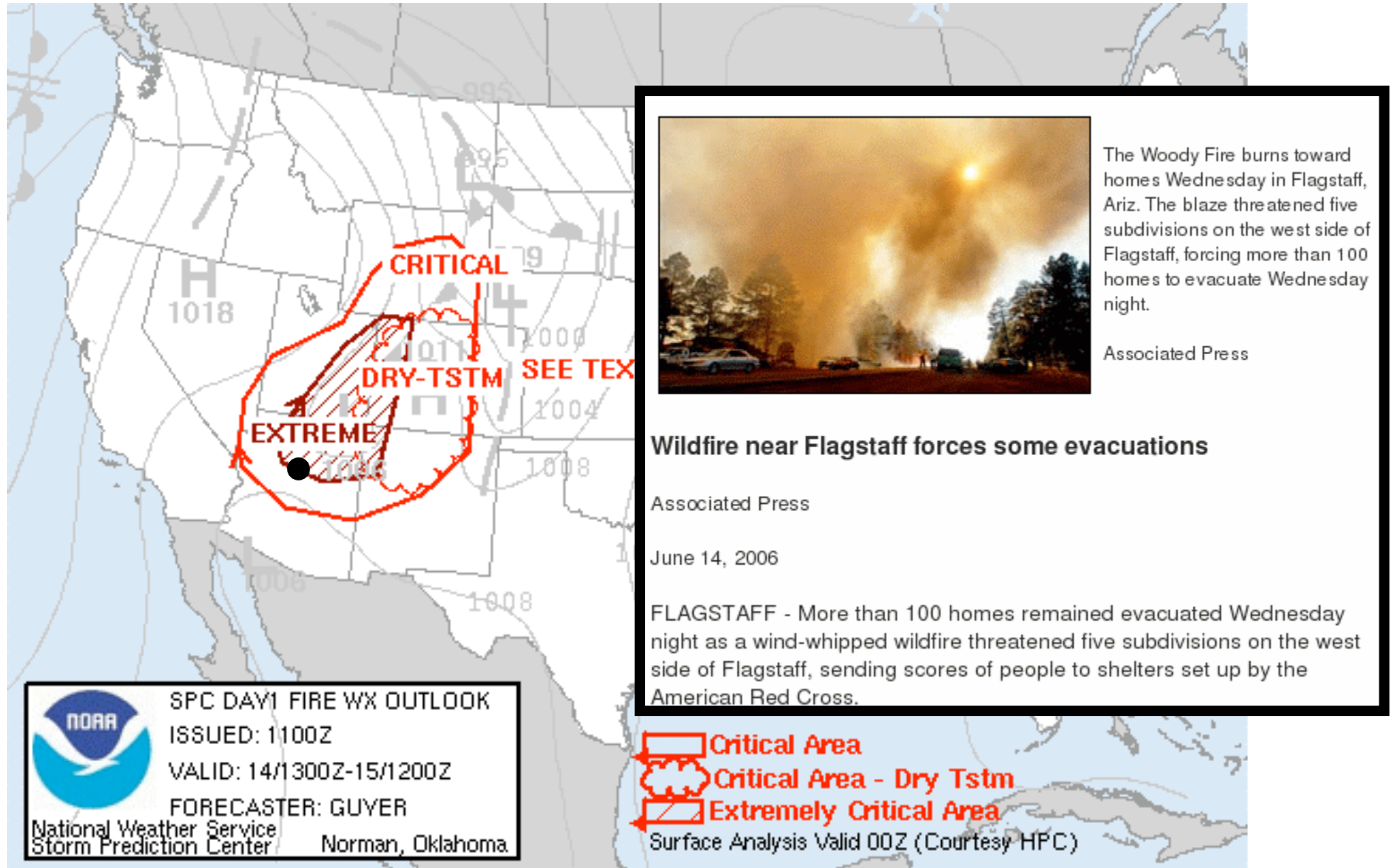
SREF Combined or Joint Probability



Joint probability of fire-weather ingredients.

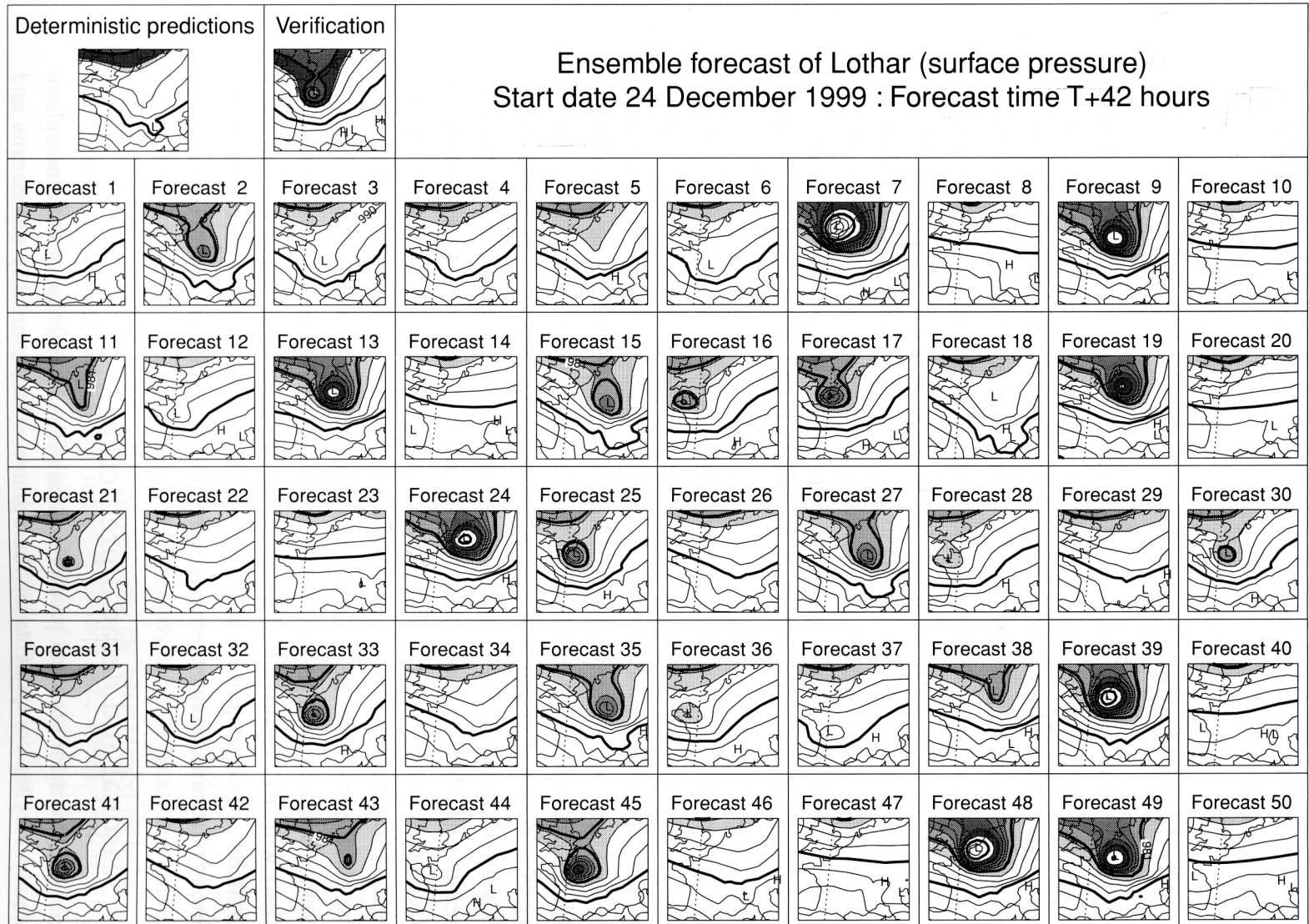
NOAA SPC Operational Outlook

(Uncertainty communicated in accompanying text)



European example: “Lothar” storm, 1999

deterministic
forecast →
totally misses
damaging
storm over
France; some
ensemble
members
forecast it
well.



from Tim Palmer's
book chapter, 2006,
in “Predictability of
Weather and
Climate”.

Dutch storm, 1 February 1953 ECMWF reanalysis & reforecast

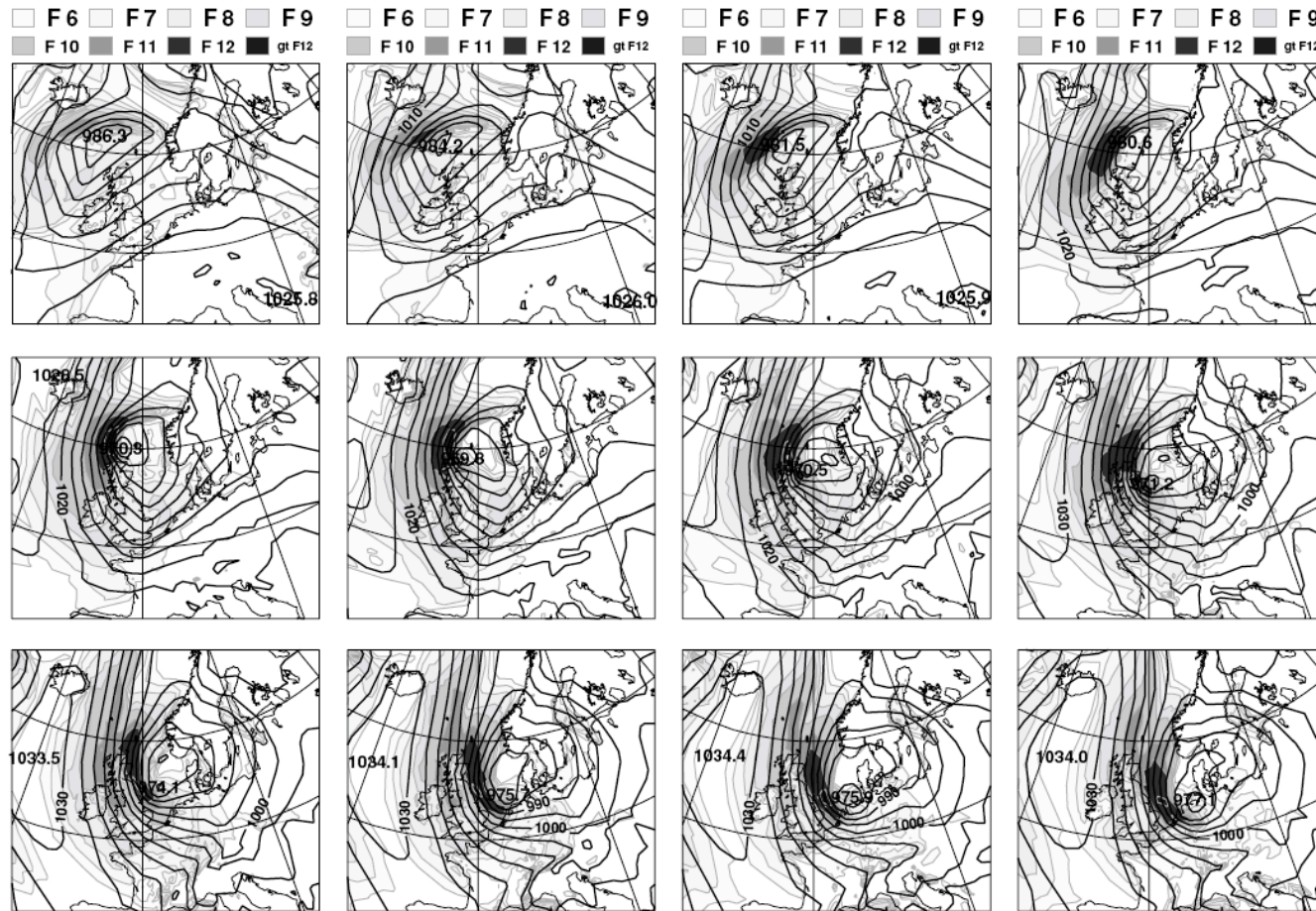


Figure 1. Mean sea level pressure (contours in hPa) and maximum wind gustiness (shading in Bft) for intervals of 3 hours from 15 UTC on 30 January 1953 (upper left panel) to 00 UTC on 1 February 1953 (lower right panel). The upper row is based on 3, 6, 9 and 12-hour forecasts using the high-resolution system (HRES in Table 1) started at 12 UTC on 30 January 1953. The middle and lower rows are based on corresponding forecasts but started at 00 UTC on 31 January and 12 UTC on 31 January 1953, respectively. Note that the maximum refers to 3-hour periods. Officially, the Beaufort scale does not have values greater than 12 Bft. Here, maximum gustiness greater than 12 Bft is used for values exceeding 40 m/s.

- Sea-level pressure analyses and Beaufort wind scales shown. Prevalence of strong onshore winds for long period of time led to catastrophic flooding in the Netherlands.
- 50 dykes burst almost simultaneously, 1850 people killed, sea-level rise not seen in 400-500 years (estimated).

Ref: Jung et al.,
Meteor. Appl.,
 2004 (part I). 20



Dutch storm, 1 February 1953 ECMWF reanalysis & reforecast

- 108-h forecast shown here. Hints in a few members of intense winds extending toward the Dutch coast.

Ref: Jung et al., *Meteor. Appl.*, 2005 (part II).

Figure 1. Verifying mean sea level pressure analysis (hPa) at 00 UTC on 1 February 1953 (upper left panel) along with corresponding 108-hour forecast started at 12 UTC on 27 January 1953. Shown is the deterministic T511 forecast (HRES), the EPS control forecast (CNTL), and 50 members of the ensemble (Forecast 1–50, ENS). Contour interval is 5 hPa.



Dutch storm, 1 February 1953 ECMWF reanalysis & reforecast

- 60-h forecast shown here. Now there are many more members with tight pressure gradients extending toward the Dutch coast.

Ref: Jung et al., *Meteor. Appl.*,
2005 (part II).

Figure 3. As Figure 1 except for 60-hour forecasts started at 12 UTC on 29 January 1953.

Dutch storm, 1 February 1953 ECMWF reanalysis & reforecast

- Probabilities from 51-member ensemble show, however, that only by 36 h in this figure do high probabilities of strong gusts extend to the Dutch coast.
- Predictability of this storm was assessed by authors as 48 h.

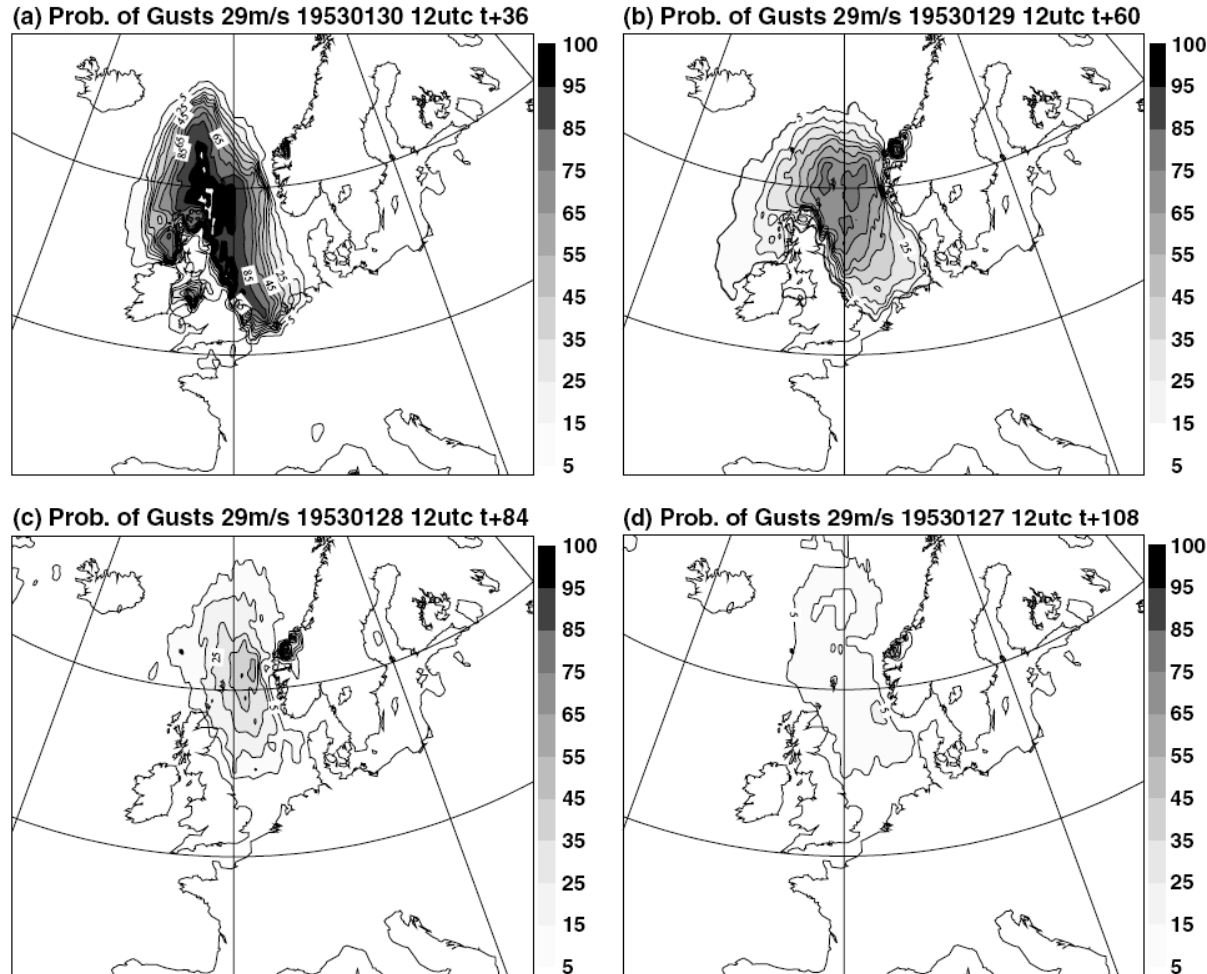
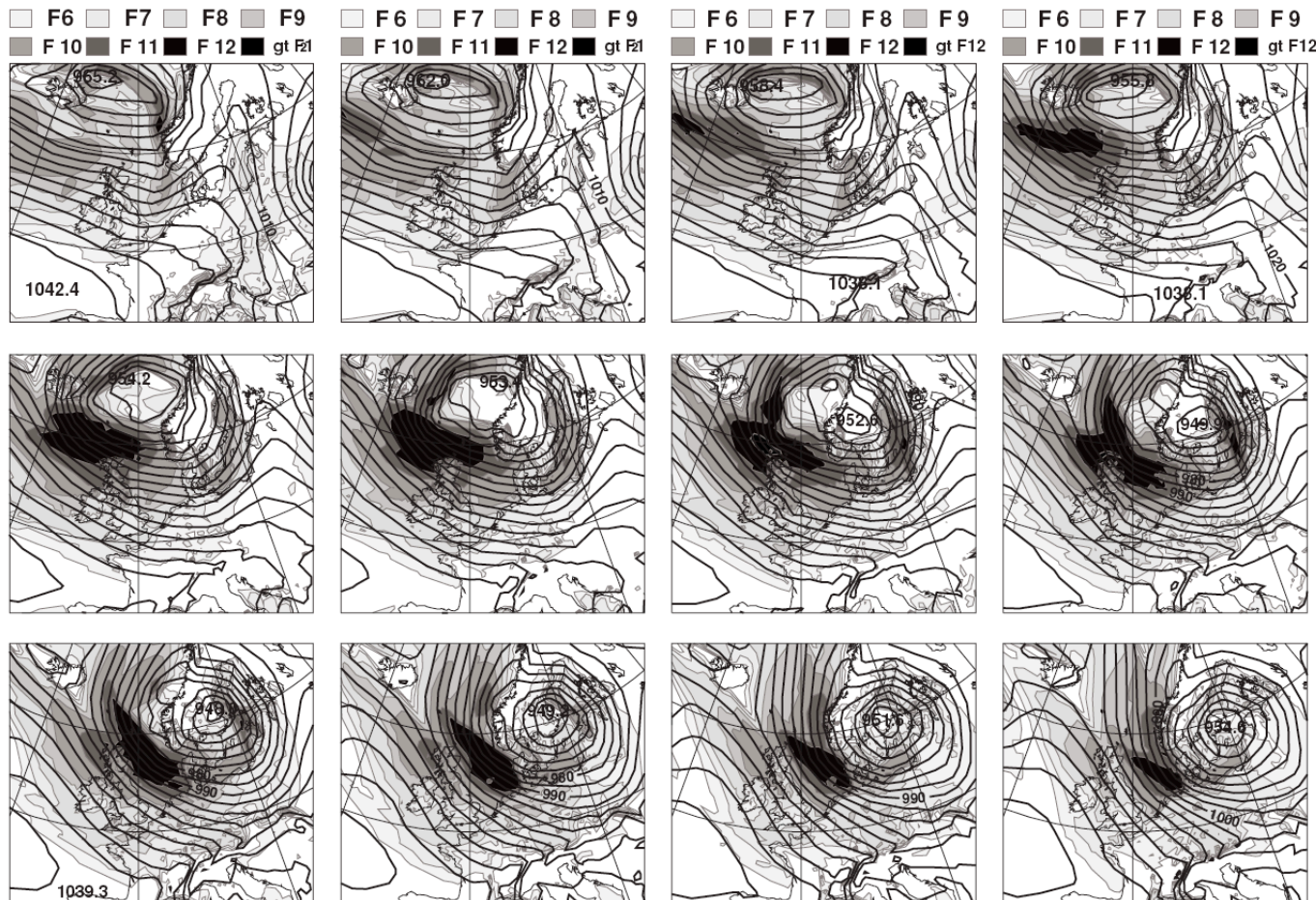


Figure 5. Probability (%) of maximum wind gusts exceeding 29 m/s (11 Bft) for (a) 36, (b) 60, (c) 84, and (d) 108-hour ensemble forecasts verifying at 00 UTC on 1 February 1953. The probabilities have been estimated using the control forecast (CNTL) along with 50 perturbed ensemble members (ENS).

Ref: Jung et al., *Meteor. Appl.*,
2005 (part II).

Hamburg storm, 17 February 1962

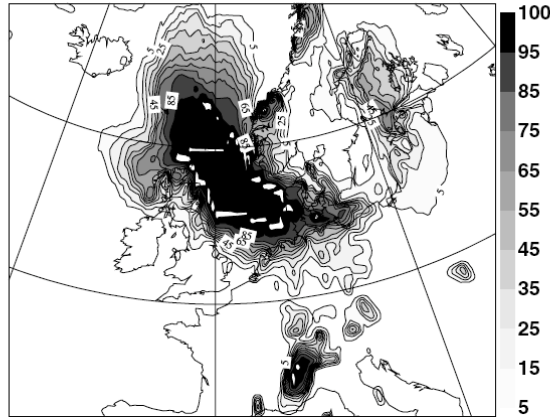


Ref: Jung et al.,
Meteor. Appl.,
2004 (part I).

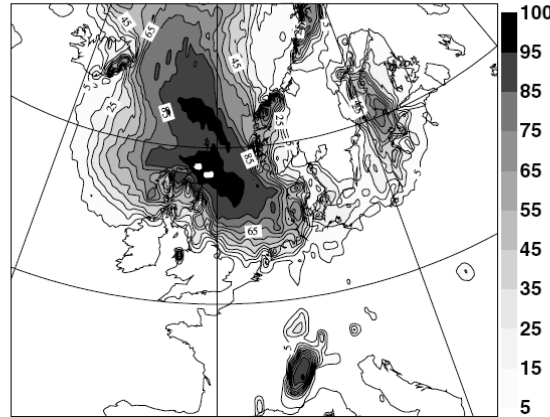
Figure 6. As for Figure 1, except for the Hamburg storm. Results are for 3-hour intervals from 15 UTC on 15 February 1962 (upper left panel) to 00 UTC on 17 February 1962 (lower right panel) using HRES.

- Here, sea-level pressure and maximum wind gustiness.
- Hamburg, 70 km upstream of mouth of Elbe, flooded on storm surge. 340 killed.

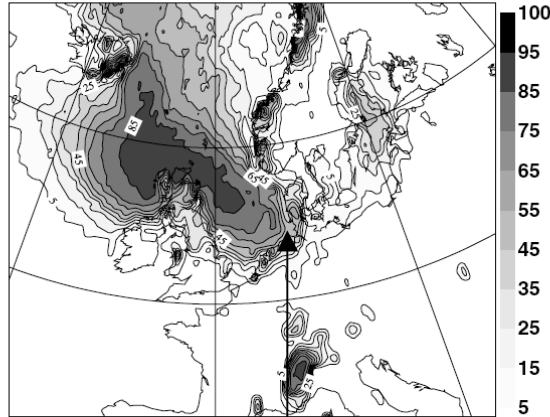
(a) Prob. of Gusts 29m/s 19620215 12utc t+36



(b) Prob. of Gusts 29m/s 19620214 12utc t+60



(c) Prob. of Gusts 29m/s 19620213 12utc t+84



(d) Prob. of Gusts 29m/s 19620212 12utc t+108

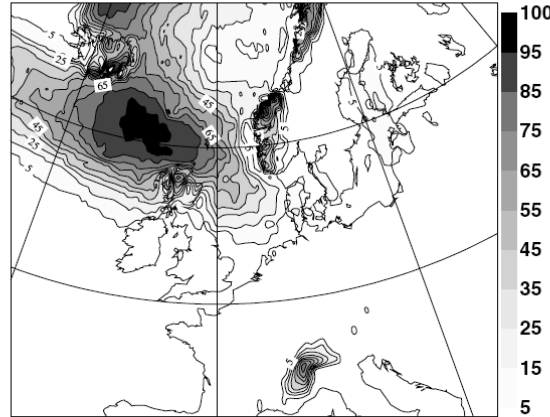


Figure 6. Probability (%) of maximum gusts greater than 29 m/s (11 Bft) for (a) 36, (b) 60, (c) 84, and (d) 108-hour forecasts verifying at 00 UTC on 17 February 1962. Probability estimates are based on the control forecast (CNTL) and all 50 ensemble members (ENS).

Hamburg storm, 17 February 1962 ECMWF reanalysis & reforecast

- Probabilities from 51-member ensemble show that by 84 h a significant fraction of members had gusts to the German coast, indicating the possibility of a storm surge up the Elbe River.
- Predictability of this storm was assessed by authors as 84 h.

Great October storm, 15-16 September 1987

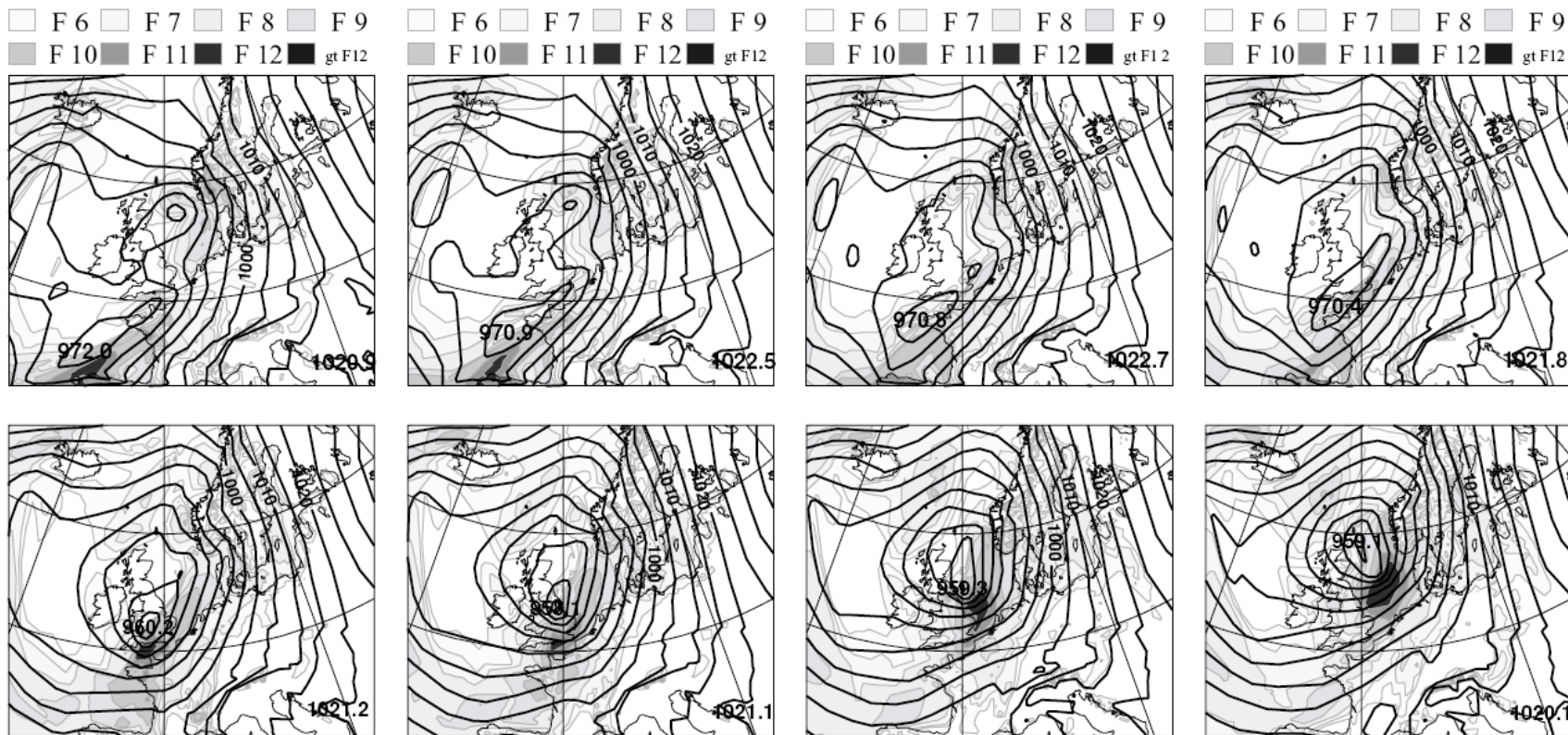
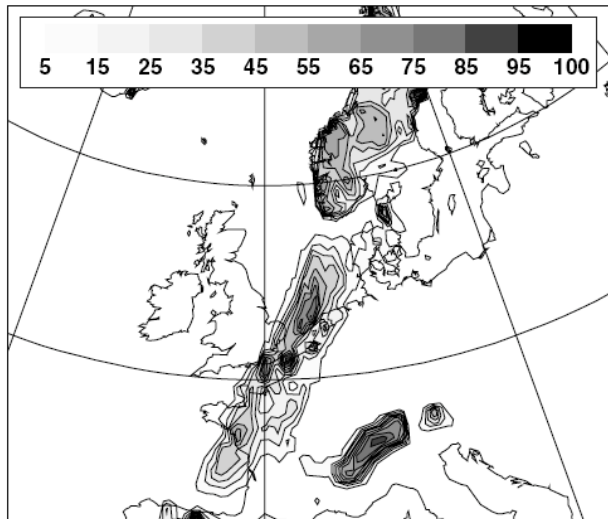


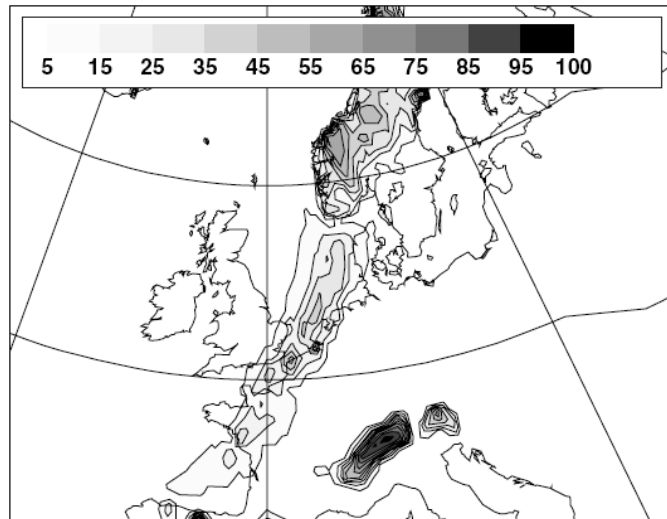
Figure 12. As for Figure 1, except for the Great October Storm. Forecasts are for intervals of 3 hours from 15 UTC on 15 October (upper left panel) to 12 UTC on 16 October 1987 (lower right panel). Note that the values are forecast (3, 6, 9, and 12-hour forecasts from left to right) using HRES.

- SE England, NW France; 20 lives lost, > \$200,000,000 damage

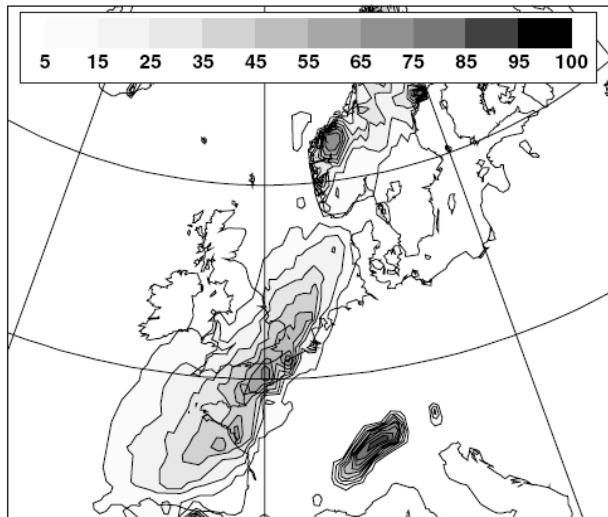
(a) Prob. of Gusts 29m/s 19871015 12utc t+24



(b) Prob. of Gusts 29m/s 19871014 12utc t+48



(c) Prob. of Gusts 29m/s 19871013 12utc t+72



(d) Prob. of Gusts 29m/s 19871012 12utc t+96

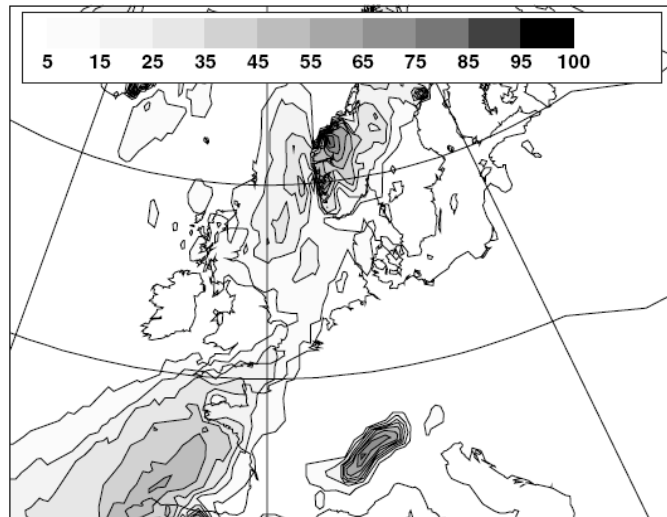


Figure 8. As Figure 7, except for (a) 24-hour, (b) 48-hour, (c) 72-hour, and (d) 96-hour forecasts verifying at 12 UTC on 16 October 1987. Maximum values of wind strength are based on the 12-hour period 00 UTC on 16 October to 12 UTC on 16 October.

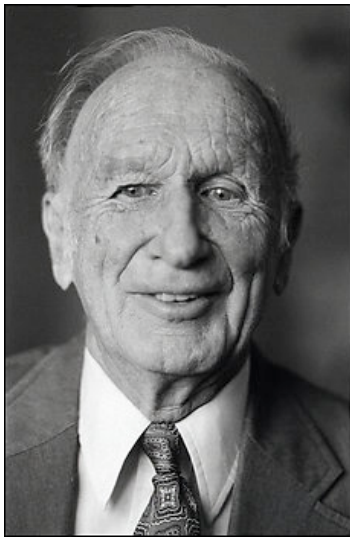
Great October storm, 15-16 September 1987 reanalysis and reforecast

- Indications of track and intensity were seen up to 96 h in advance, according to authors.

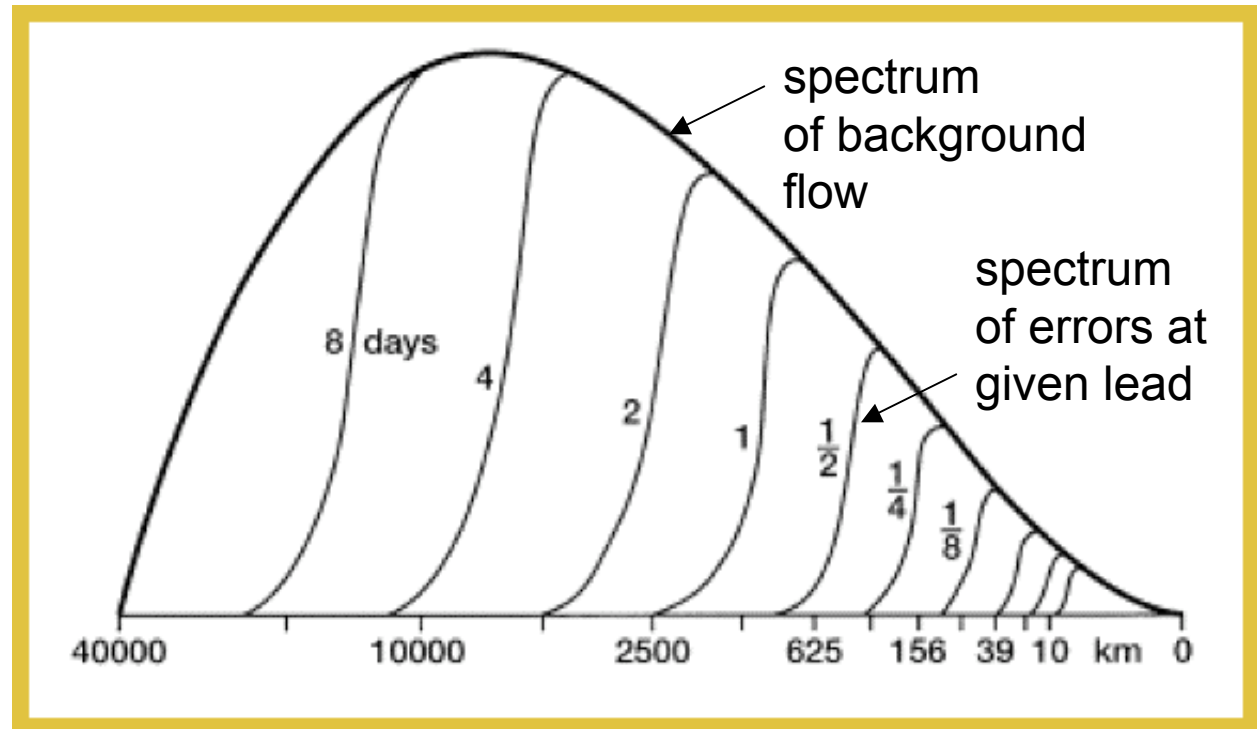
What about predictability of
extreme weather events from
small-scale features?

Lorenz's 1969 “*Predictability of flow possessing many scales of motion*”

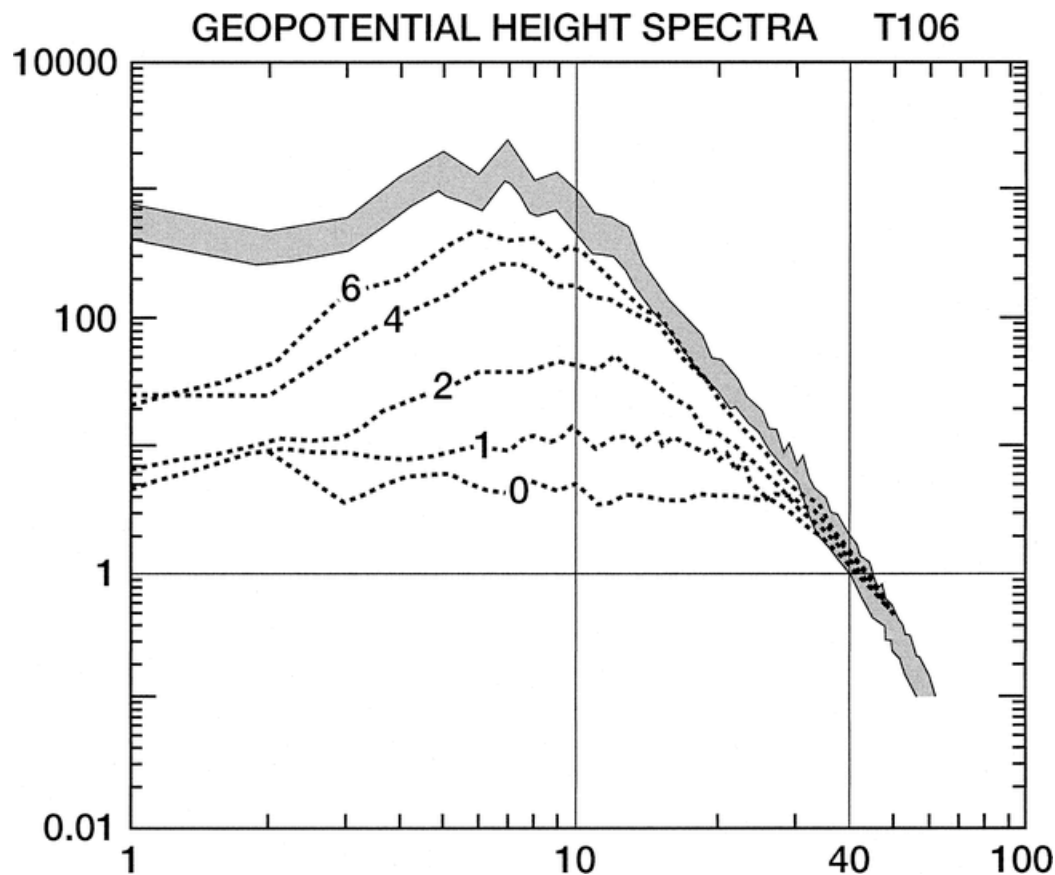
- Simple system with $E_k \propto k^{-5/3}$ in sub-synoptic scales
- Suppositions: small scales saturate quickly, errors spread upscale.



Ed Lorenz,
1918-2008



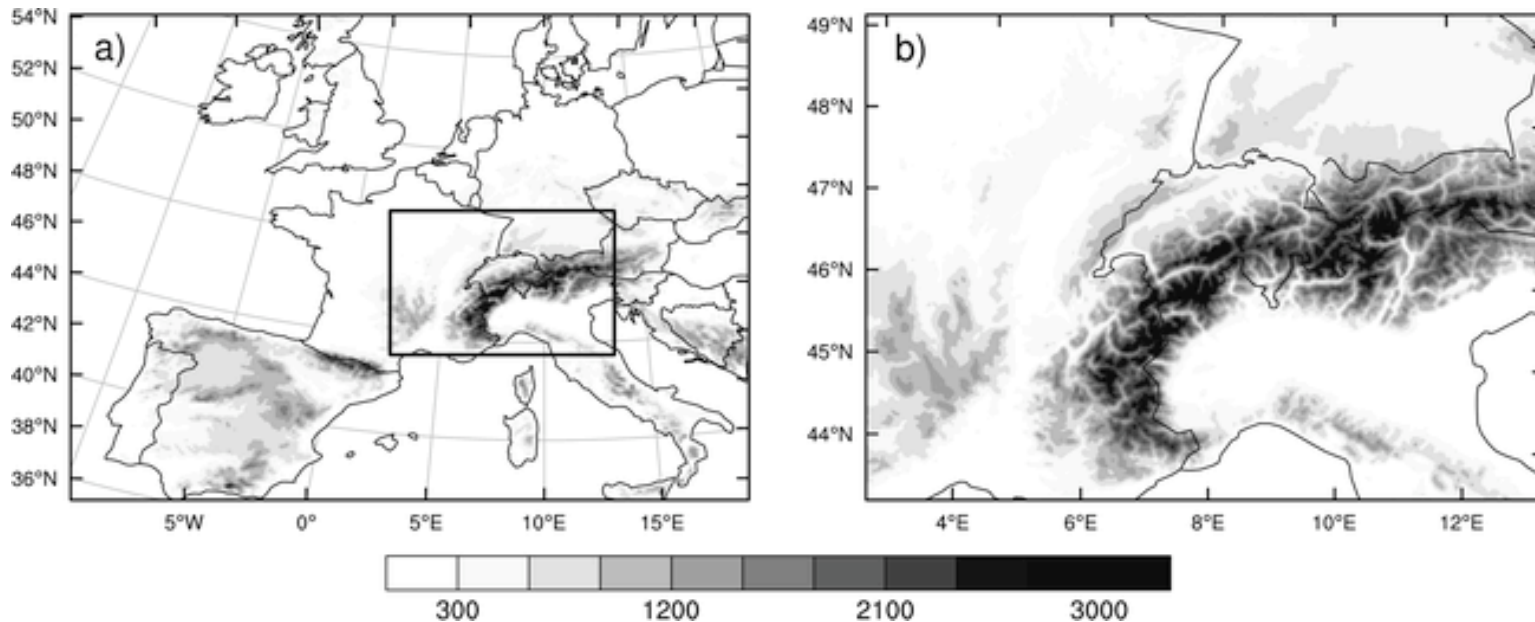
Predictability theory, updated



Errors in small scales grow very rapidly, until they project on synoptic scales. Thereafter, slower, more modal growth.

...but this doesn't really provide intuition about situations when intense mesoscale features are predictable and when they are not.

Understanding predictable and less predictable intense precipitation events in the Alps

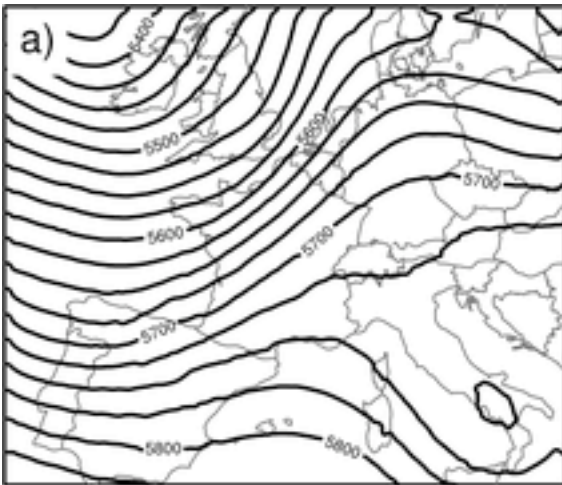


- Integration domains and topography (m) of the (a) 7- and (b) 2.2-km LM simulations. Six-member ensemble in the interior domain using shifting initialization times. LBCs for larger domain from ECMWF forecast.

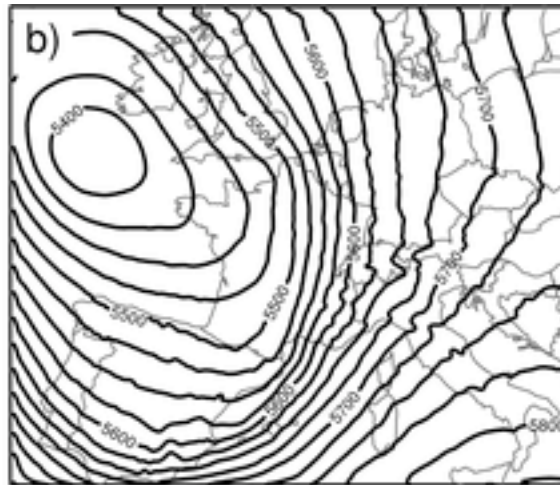
Understanding predictable and less predictable intense precipitation events in the Alps

500-hPa initial conditions for 3 cases

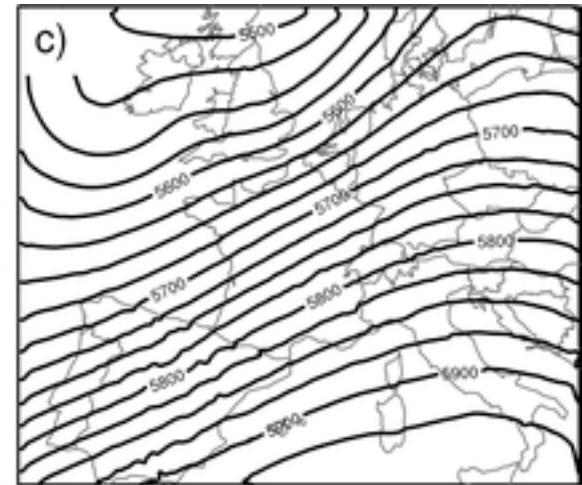
IOP2a: 00 UTC 17 Sep 1999



IOP 2b: 00 UTC 20 Sep 1999

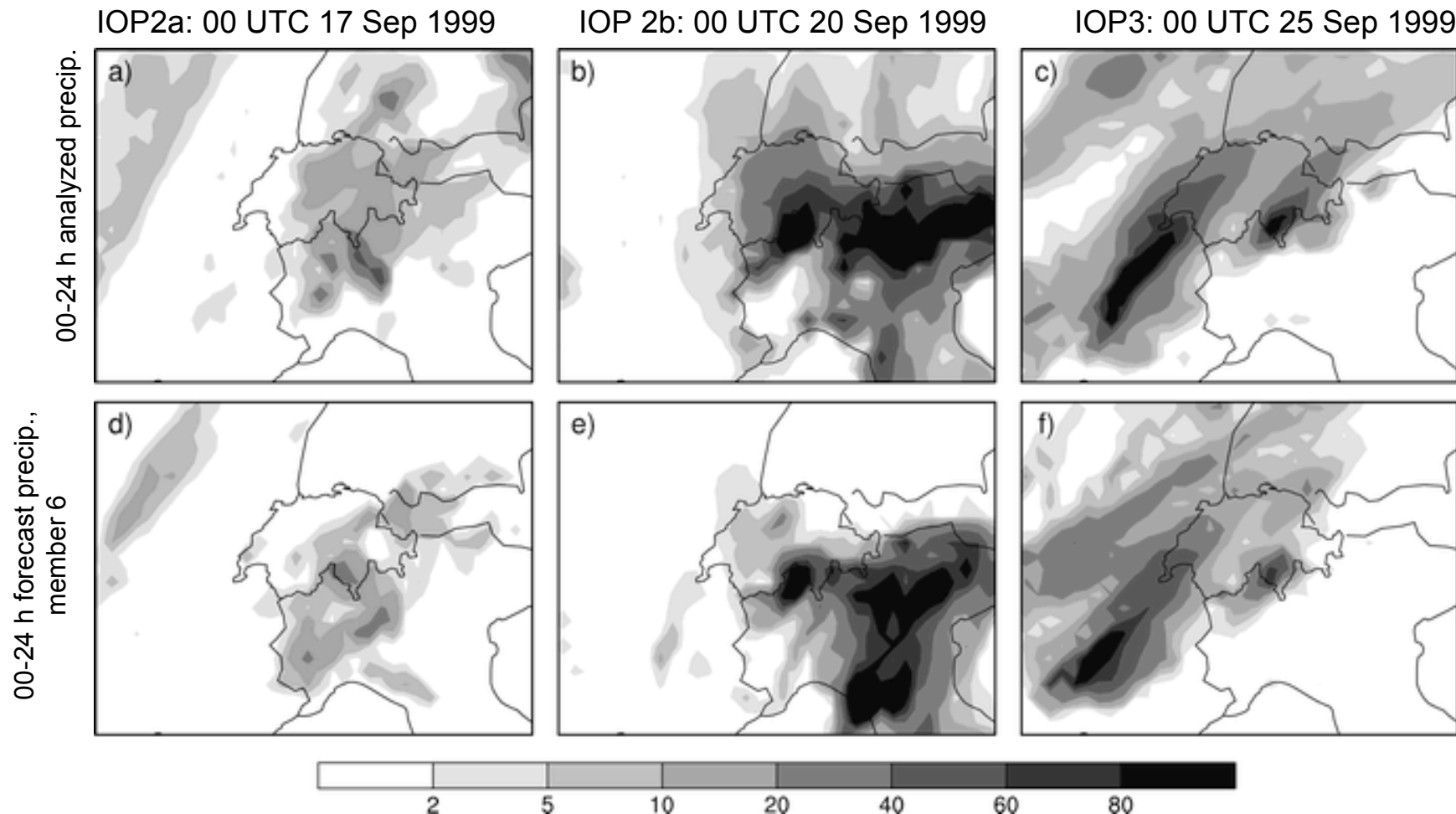


IOP3: 00 UTC 25 Sep 1999



- Data from Mesoscale Alpine Program (MAP), Bougeault et al., *BAMS*, 2001.

Understanding predictable and less predictable intense precipitation events in the Alps



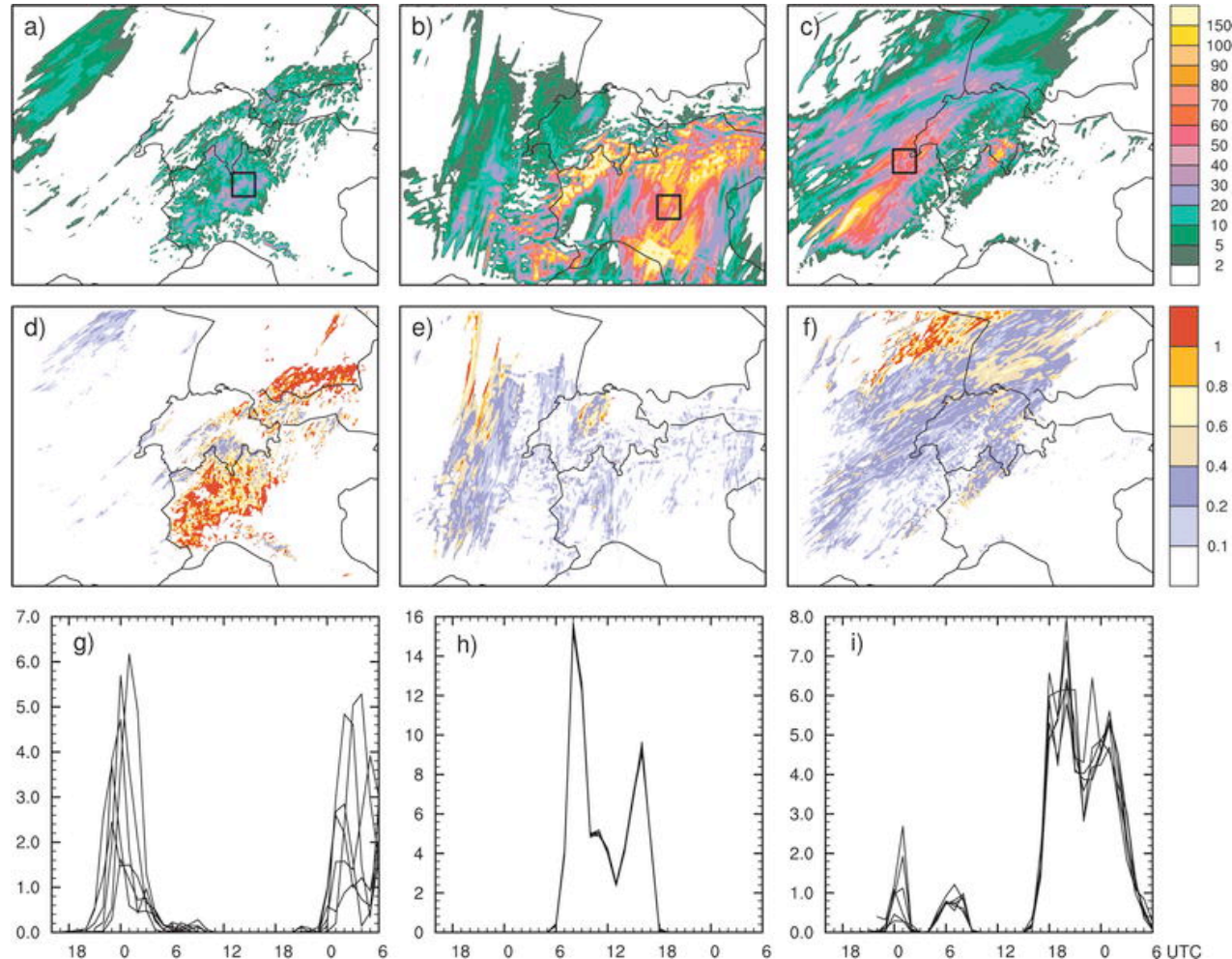
- Reasonable correspondence between model forecast and analyzed precipitations.

Understanding predictable and less predictable intense precipitation events in the Alps

IOP2a: 00 UTC 17 Sep 1999

IOP 2b: 00 UTC 20 Sep 1999

IOP3: 00 UTC 25 Sep 1999



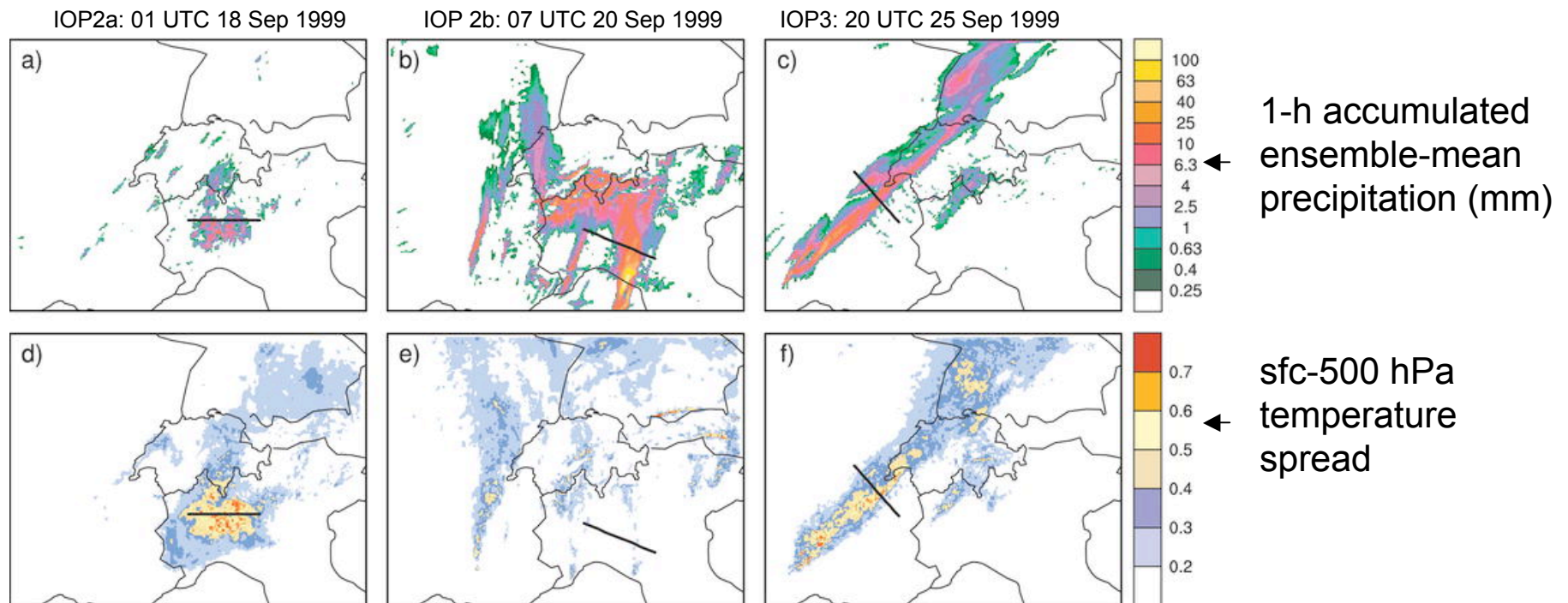
30-h accumulated
ensemble-mean
precipitation (mm)

30-h normalized
precipitation
spread

time series for
each member in
boxed regions

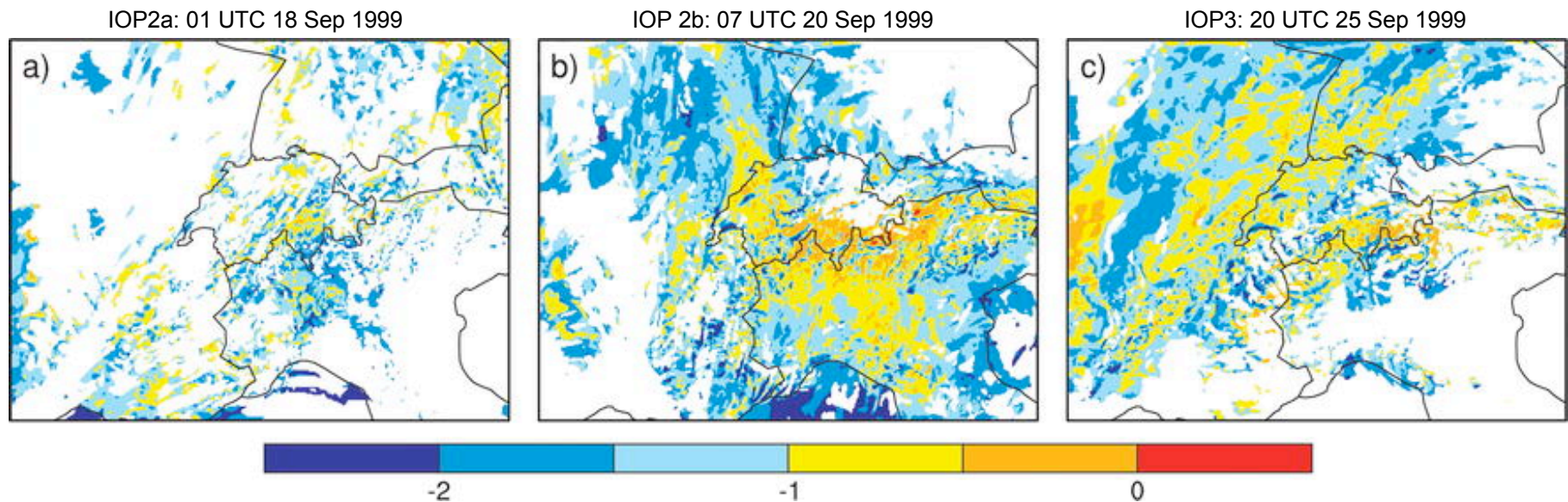
- Normalized spread: IOP2a > IOP3 >> IOP2b. Why?

Understanding predictable and less predictable intense precipitation events in the Alps



- Temperature spread particularly small in IOP2b's precipitation region. Why?

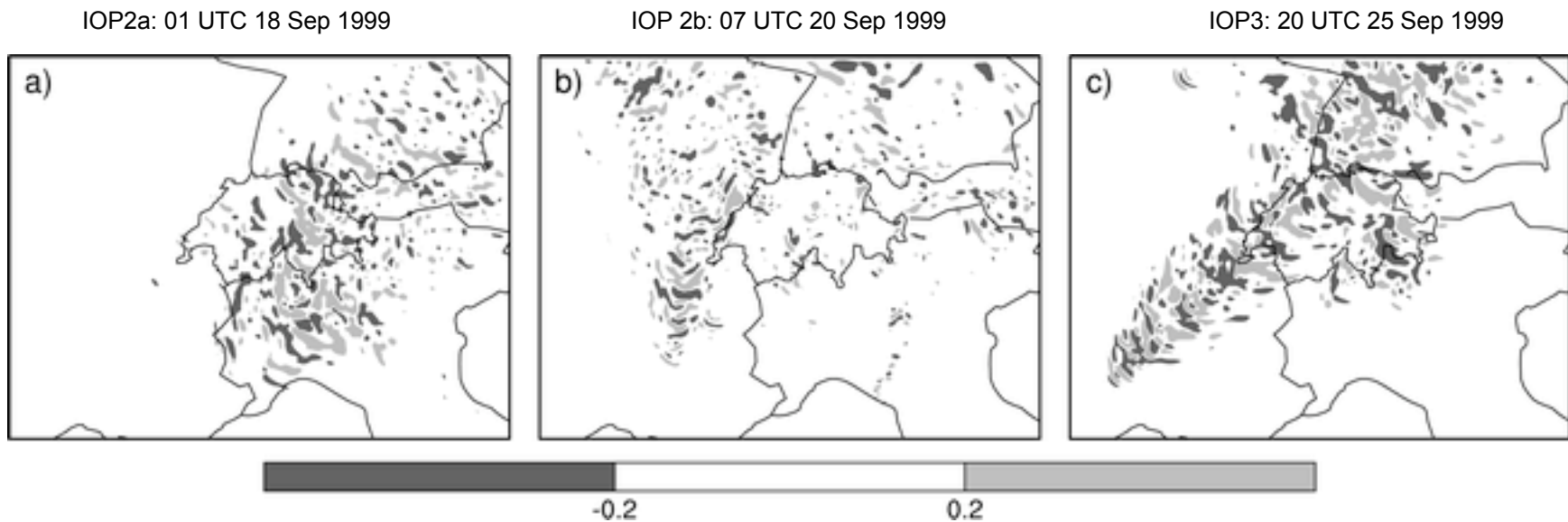
Understanding predictable and less predictable intense precipitation events in the Alps



Vertical minimum of the moist Brunt–Väisälä frequency N_m^2 (10^{-4} s^{-2}) derived for ensemble member 6. Cloud-free grid points are masked in white.

- IOP2b has plenty of moist instability relative to the other IOPs, so instability is not the source of unpredictability.

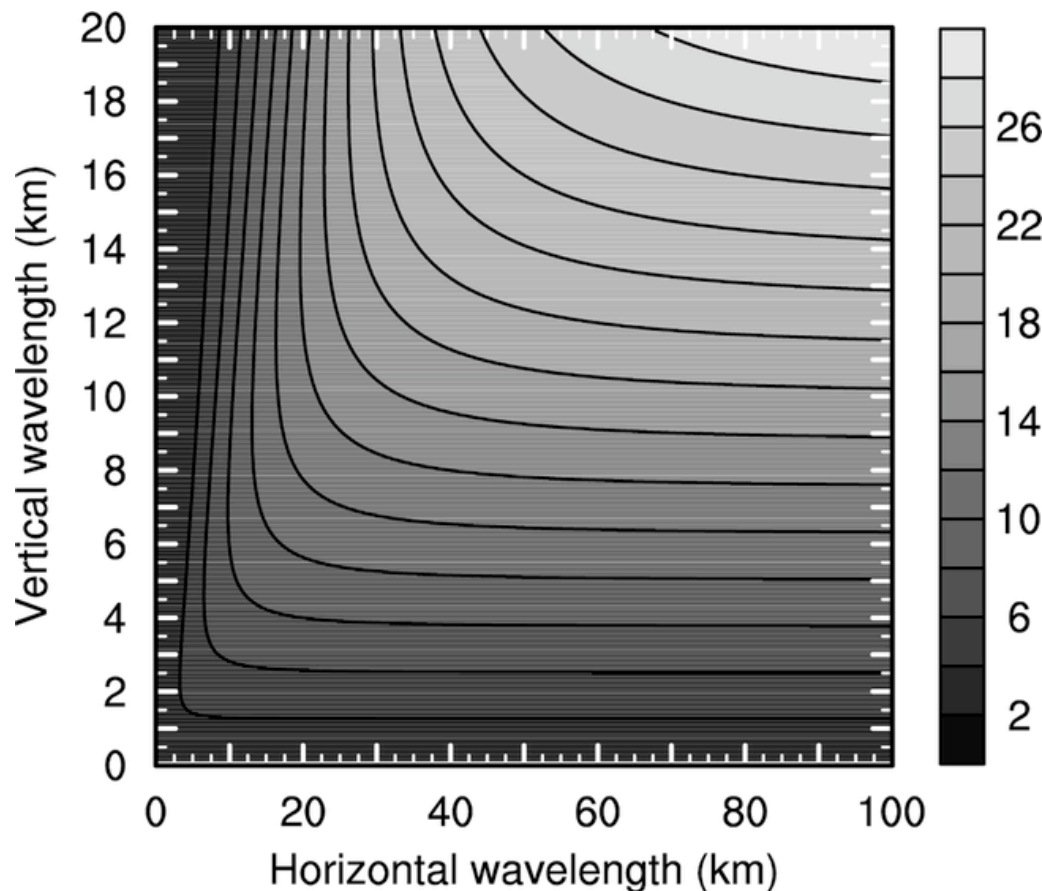
Understanding predictable and less predictable intense precipitation events in the Alps



Temperature difference (K) between ensemble members 5 and 6 at a height of 13.6 km.

- Perturbations related to internal gravity wave activity.

Understanding predictable and less predictable intense precipitation events in the Alps



Theoretically derived critical wind speed U_{crit} (m s^{-1}) allowing upstream propagation of energy as a function of horizontal and vertical wavelengths and for $N = 0.01 \text{ s}^{-1}$ [see Eq. (4)]

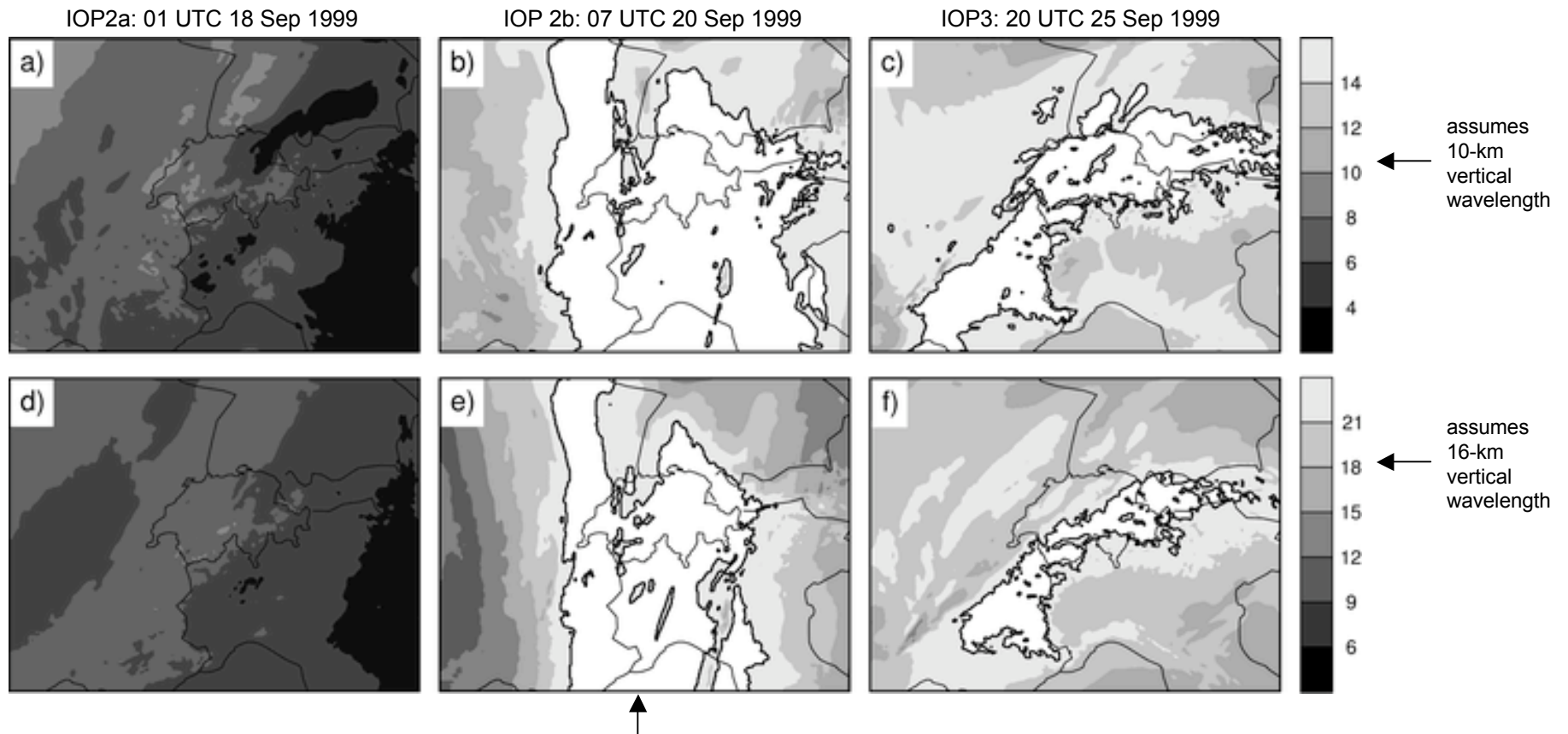
Consider propagation of gravity waves in a dry airstream, uniform stratification and windspeed. Linear analysis as in Holton text (2004, eq. 7.45a)

$$U_o \leq \frac{Nm^2}{(m^2 + k^2)\sqrt{m^2 + k^2}} = U_{\text{crit}}. \quad (4)$$

where k and m are the vertical and horizontal wavenumber, N^2 is Brunt-Väisälä frequency. **When windspeed is less than critical, gravity waves can propagate against mean flow and stay in source region long enough to grow, else they are swept out of growth region.** Plot shows that deep gravity waves have higher critical speed threshold and can propagate upstream under broader range of conditions.

Understanding predictable and less predictable intense precipitation events in the Alps

Ensemble mean of the horizontal wind velocity U_o (m s^{-1}). Values larger than U_{crit} inhibiting upstream energy propagation are masked in white. Values for U_o and N have been averaged over half a vertical wavelength.



IOP2b's winds above critical threshold, prohibiting local growth of perturbations from gravity-wave activity.

Synthesizing Hohnegger et al.

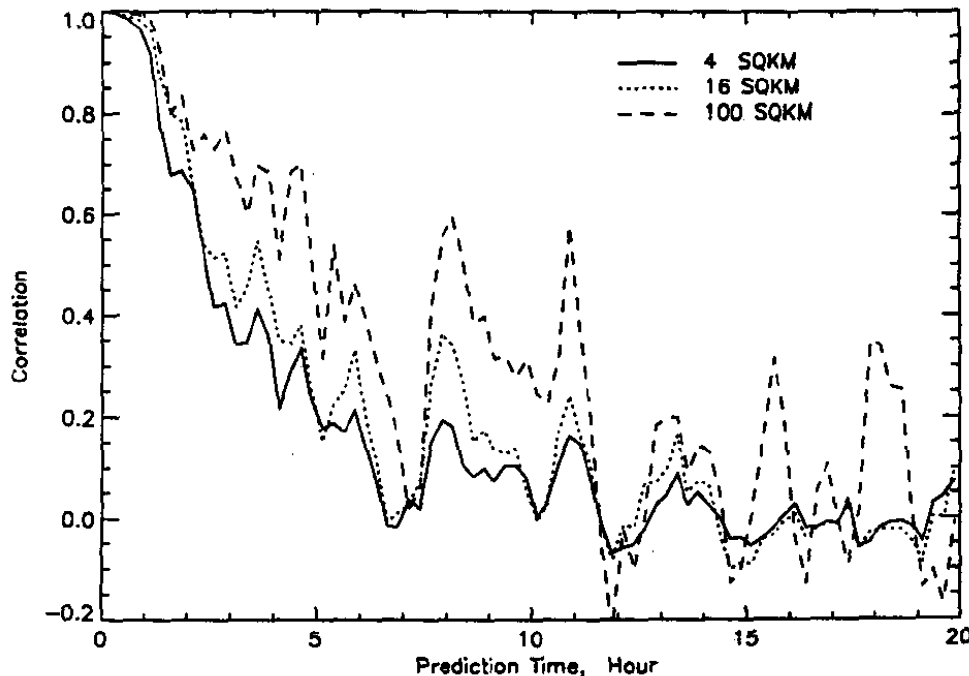
- Mesoscale perturbations get stimulated in regions of moist convection¹.
- Perturbations may grow locally if they can remain in a region of moist instability, reducing predictability. High wind speeds tend to sweep the nascent perturbations away from genesis region.²
- Reinforces hypothesis that mesoscale predictability is lengthened when large-scale forcing is strong.

¹ See also Zhang et al. 2003 *JAS*, Bei and Zhang, *QJRM*S, 2007.

² See also Huerre and Monkewitz 1985 *J. Fluid Mech*, Snyder and Joly 1998 *QJRM*S, and literature on “local baroclinic instability”

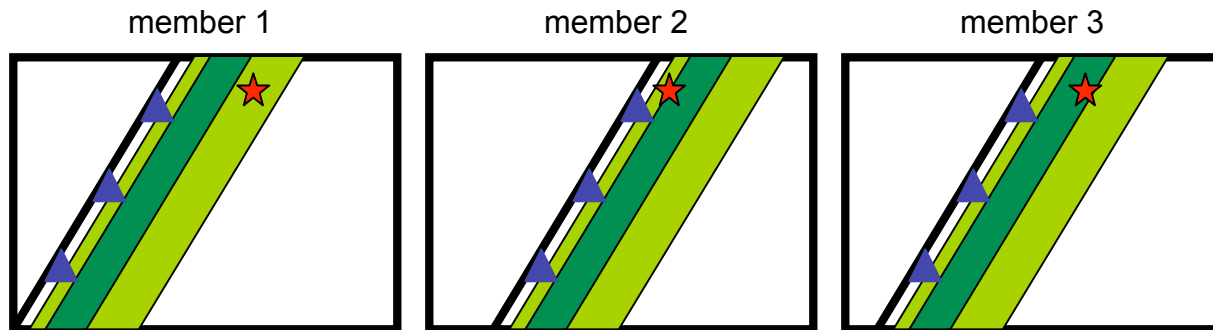
Predictability of convective precipitation without large-scale forcing

Correlation between control and perturbed rainfall field for 15-min. accumulations.

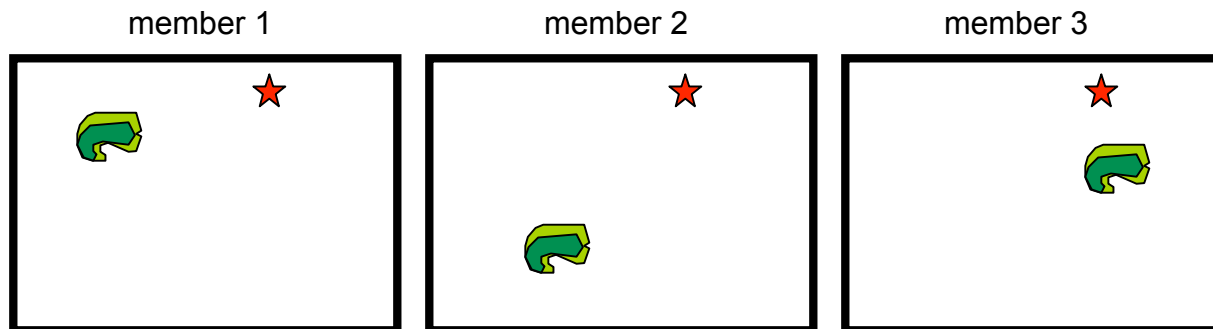


- Tropical simulation of convection using grid point model with periodic boundary conditions, integrated to statistical equilibrium. Then control and slightly perturbed simulations are compared.
- Main points:
 - Without large-scale external forcing, small-scale convective precipitation predictability lost in ~ 6h, more consistent with Lorenz 1969. Much faster than baroclinic scales.
 - Averaging over larger grid areas results in enhanced estimates of predictability.

Sample-size issues



- Size of feature approximately the same as spatial variations between members. Moderately sized ensemble **adequate** for estimating probabilities



- Size of feature much smaller than spatial variations between members. Moderately sized ensemble **inadequate** for estimating probabilities. Either large ensemble, or statistical adjustment necessary.

Synthesis

- If extreme events are driven by large scales and for phenomena that are not particularly sensitive to model error → days of predictability.
- If extreme events are from mesoscale events more divorced from large scales, or if related to phenomena with large model errors → hours of predictability. May have better luck with nowcast/extrapolation techniques.